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Multispectral Observations and Analysis of the Rosette Nebula

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Jeremy Huber, Student
Dr. John Kielkopf, Major Professor
Dr. Christopher Crawford, Director of Graduate Studies
MULTISPECTRAL OBSERVATIONS AND ANALYSIS OF THE ROSETTE NEBULA

DISSEhATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Arts and Sciences at the University of Kentucky

By
Jeremy Huber
Lexington, Kentucky

Director: Dr. Dr. John Kielkopf, Professor of Physics and Astronomy
Co-Director: Dr. Dr. Gary Ferland, Professor of Physics and Astronomy
Lexington, Kentucky 2017

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ABSTRACT OF DISSERTATION

MULTISPECTRAL OBSERVATIONS AND ANALYSIS OF THE ROSETTE NEBULA

The Rosette nebula is a large, ring-shaped emission nebula with a distinctive central cavity excavated by its central cluster of OB stars. Toward understanding the three dimensional structure and fundamental physical processes of this object, we have acquired flux-calibrated, 4-degree field, deep exposures of the Rosette region through 3 nm bandwidth Hα (656.3 nm) as well as Hβ (486.1 nm), [OIII] (500.7 nm) and [SII] (671.6 nm) filters with 4.5 nm bandwidth. The 4 arcsec/pixel images are supplemented with 4 degree field slit spectra and combined with archival data from the Galactic Evolution Explorer satellite (GALEX), Akari, the Infrared Astronomical Satellite (IRAS), the Midcourse Space Experiment (MSX), the Wide-field Infrared Survey Explorer (WISE), the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck mission, along with published single dish radio data of the hydrogen continuum at 1410, 2700, and 4750 MHz. These disparate sources have been converted to the same flux and spatial scale as our own wide field data to create a multispectral data cube which allows comparative analysis across the electromagnetic spectrum. Using ratios of data cube slices, spatial maps of extinction and ionization have been constructed to explore the spatial variation of these parameters across the nebula. Comparison of emission in different wavelengths across the data cube allows generation of a spectral energy distribution (SED) to probe dust temperature and geometry. A radial profile analysis of emission from the Rosette in each band supports a spherical shell model of three dimensional structure, and visual representations of this model have been generated in both Python and Javascript/GLSL. An investigation of anomalous dust emission in the center of the nebula via supplemental spectroscopy, conducted on the Anglo-Australian Telescope, is also presented.

KEYWORDS: HII Region, Rosette Nebula, Extinction, Ionization, Nebula Morphology

Author’s signature: Jeremy Huber

Date: April 25, 2017
MULTISPECTRAL OBSERVATIONS AND ANALYSIS OF THE ROSETTE NEBULA

By

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Date: April 25, 2017
For Heather, who knows why.
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This project was supported in part by NASA Kentucky through the Kentucky Space Grant Consortium.

With a multispectral survey of this kind, there is also an enormous list of archival resources, services, and software to thank:

This research made use of data provided by Astrometry.net.

This work has made use of NASA’s Astrophysics Data System [137], the SIMBAD database operated at CDS, Strasbourg, France [23], and the ESO Archive [49].

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France

Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts.
This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA), part of the High Energy Astrophysics Science Archive Center (HEASARC). HEASARC/LAMBDA is a service of the Astrophysics Science Division at the NASA Goddard Space Flight Center.

Partly based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg.

This dissertation makes use of data products from Wilkinson Microwave Anisotropy Probe, operated by NASA.

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Acknowledgments</th>
<th>iii</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table of Contents</td>
<td>vi</td>
</tr>
<tr>
<td>List of Tables</td>
<td>ix</td>
</tr>
<tr>
<td>List of Figures</td>
<td>xi</td>
</tr>
<tr>
<td><strong>Chapter 1  Introduction</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Overview</td>
<td>1</td>
</tr>
<tr>
<td>1.2 HII Regions</td>
<td>4</td>
</tr>
<tr>
<td>1.3 Central Cluster</td>
<td>5</td>
</tr>
<tr>
<td>1.4 Dust and Mid IR Emission</td>
<td>8</td>
</tr>
<tr>
<td>1.5 The Rosette Molecular Complex</td>
<td>10</td>
</tr>
<tr>
<td>1.6 Star Formation</td>
<td>12</td>
</tr>
<tr>
<td>1.7 Elephant Trunks and Globulettles</td>
<td>13</td>
</tr>
<tr>
<td><strong>Chapter 2  Observations</strong></td>
<td>16</td>
</tr>
<tr>
<td>2.1 Instrumentation</td>
<td>16</td>
</tr>
<tr>
<td>2.2 Wide-field Database</td>
<td>18</td>
</tr>
<tr>
<td>2.3 High Spatial Resolution Images</td>
<td>23</td>
</tr>
<tr>
<td>2.4 Spectral Images</td>
<td>23</td>
</tr>
<tr>
<td><strong>Chapter 3  Atmospheric Effects and Spectral Calibration</strong></td>
<td>30</td>
</tr>
<tr>
<td>3.1 Determining Extinction Per Air Mass</td>
<td>30</td>
</tr>
<tr>
<td>3.2 Effective Exposure Time Calculation</td>
<td>31</td>
</tr>
<tr>
<td>3.3 WISPI Calibration</td>
<td>34</td>
</tr>
<tr>
<td><strong>Chapter 4  Flux Calibration of Wide Field Data</strong></td>
<td>41</td>
</tr>
<tr>
<td>4.1 Calibration from NGC 7000</td>
<td>41</td>
</tr>
<tr>
<td>4.2 Calibration from WISPI</td>
<td>42</td>
</tr>
<tr>
<td>4.3 WISPI Air Mass Considerations</td>
<td>51</td>
</tr>
<tr>
<td>4.4 Uncertainty in the Narrow Band Images</td>
<td>52</td>
</tr>
<tr>
<td><strong>Chapter 5  Multispectral Data from Archival Resources</strong></td>
<td>57</td>
</tr>
<tr>
<td>5.1 Effelsberg 100 m Observations</td>
<td>58</td>
</tr>
<tr>
<td>5.2 Wilkinson Microwave Anisotropy Probe (WMAP) Observations</td>
<td>62</td>
</tr>
<tr>
<td>5.3 Planck Observations</td>
<td>65</td>
</tr>
<tr>
<td>5.4 Akari Observations</td>
<td>67</td>
</tr>
<tr>
<td>5.5 Infrared Astronomical Satellite (IRAS) Observations</td>
<td>71</td>
</tr>
<tr>
<td>5.6 Midcourse Space Experiment (MSX) Observations</td>
<td>72</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

2.1 Narrow Band Filters .......................................................... 16
2.2 Collected Wide Field Data .................................................... 21
2.3 Wide Field Data Products ..................................................... 22
2.4 WISPI Data Summary .......................................................... 26
2.5 WISPI Data Products .......................................................... 26

3.1 Airmass Magnitude Change By Filter ....................................... 31
3.2 Effective Exposure Times ..................................................... 34

4.1 Wide Field Calibration .......................................................... 51
4.2 Wide Field Calibration With WISPI Airmass .......................... 52
4.3 Astrometric Uncertainty Target Comparison .......................... 53
4.4 Statistical Noise Determination ............................................ 54
4.5 Airmass Contributions to Absolute Flux Uncertainties .......... 55
4.6 Wide Field Absolute Flux Uncertainties ............................... 56

5.1 Data Cube Inventory .......................................................... 59
5.2 Effelsberg 100 m Bands ......................................................... 61
5.3 Effelsberg 100 m Unit Conversion .......................................... 62
5.4 Effelsberg 100m Uncertainties ............................................. 64
5.5 WMAP Unit Conversion 1 ...................................................... 64
5.6 WMAP Unit Conversion 2 ...................................................... 65
5.7 Planck High Frequency Unit Conversion 1 ............................ 66
5.8 Planck Mid and Low Frequency Unit Conversion .................. 67
5.9 Planck Uncertainties .......................................................... 69
5.10 Akari Unit Conversion ......................................................... 69
5.11 Akari Uncertainties .......................................................... 71
5.12 IRAS Uncertainties ........................................................... 72
5.13 IRAS Unit Conversion ......................................................... 72
5.14 WISE Unit Conversion ....................................................... 76
5.15 FSQ Unit Conversion ........................................................ 79

6.1 Narrowband Extinction Relative to A(V) ............................... 120
6.2 Magnitude Reddening for Narrowband Ratios ....................... 122

7.1 Cluster Membership for GSC 00154-01819 ............................ 135
7.2 Available Rosette Stellar Spectra ......................................... 136
7.3 GSC 00154-01819 Archival Data ........................................... 137
7.4 Spectra of GSC 00154-01819 with the AAT UCLES from Program UC 208 139
7.5 Radial velocity of GSC 00154-01819 .................................. 150
7.6 New data on GSC 00154-01819 ........................................... 151
7.7 GSC 00154-01819 colors ..................................................... 155
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.8 GSC 00154-01819 Potential Emission Lines</td>
<td>157</td>
</tr>
<tr>
<td>7.9 GSC 00154-01819 Nebula Background</td>
<td>162</td>
</tr>
<tr>
<td>9.1 Star Mask Component Slices</td>
<td>169</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

1.1 Rosette Tricolor ............................................. 2
1.2 Rosette Region Map ........................................... 3
1.3 NGC 2244 O Stars ............................................. 6
1.4 Rosette Herschel Composite .................................. 10
1.5 Rosette Globulettes .......................................... 15

2.1 FSQ Image ....................................................... 17
2.2 FSQ Schematic .................................................. 17
2.3 WISPI Image ..................................................... 19
2.4 WISPI Schematic ................................................ 20
2.5 Rosette Hα ....................................................... 21
2.6 North America Nebula Hα ...................................... 22
2.7 Processing Flow Chart ......................................... 24
2.8 BVRI Elephant Trunks .......................................... 25
2.9 WISPI Raw Data .................................................. 27
2.10 WISPI Plot 1 ..................................................... 28
2.11 WISPI Plot 2 ..................................................... 29

3.1 Magnitude vs. Air Mass Fitting in Hα .......................... 32
3.2 Magnitude vs. Air Mass Correction in Hα ......................... 35
3.3 WISPI Vega Image ............................................... 36
3.4 WISPI Fraction of Transmitted Light .......................... 37
3.5 WISPI Vega Focus Error ......................................... 38
3.6 WISPI Vega Spectrum Comparison ............................ 39
3.7 WISPI Spectral Calibration ...................................... 40

4.1 NGC 7000 Flux Sample ......................................... 43
4.2 FSQ Sample Region .............................................. 44
4.3 WISPI Sample Region ........................................... 45
4.4 Peak Analysis .................................................... 46
4.5 NGC 7000 Flux Calibrated Masters ............................ 47
4.6 M42 Flux Calibrated Masters .................................... 48
4.7 NGC 7000 False Color Mosaic .................................. 49
4.8 M42 False Color Mosaic ......................................... 50

5.1 Rosette Band Coverage ......................................... 60
5.2 Rosette Radio Maps .............................................. 63
5.3 Rosette WMAP Images .......................................... 66
5.4 Rosette Planck Images .......................................... 68
5.5 Rosette Akari Images ............................................ 70
5.6 Rosette IRAS Images ............................................. 73
Chapter 1 Introduction

1.1 Overview

The Rosette Nebula (NGC 2237-39, 44, 46) is a large and distinctive ring-shaped HII region occupying better than a degree of the northern sky. It is situated just south of the galactic plane in the constellation Monoceros. The center of the nebula has been hollowed out by a large cluster of young O and B type stars in the stellar cluster known as NGC 2244 [44]. The optical nebula is located at the northwestern tip of the massive Rosette molecular cloud, [26] and is bounded along its southern and southeastern edges by dense HI, molecular hydrogen, and dust. The Rosette molecular complex, as a whole, is one of the largest giant molecular cloud complexes in the Milky Way. The densest part of the Rosette molecular cloud lies to the southeast of the optical nebula. [81], and the complex, dusty boundary between the two is clearly visible in optical imagery. The molecular cloud also contains at least two other embedded emission nebulae, cataloged as Sharpless 280 and 282, driven by young stars collapsed from the surrounding hydrogen.

The Rosette molecular complex, and the nebula itself, appear to be intersected in the north east by the Monoceros loop supernova remnant (SNR), centered at right ascension 6h 38m 43s and declination +06° 30′ 12″ [64]. The bulk of this feature is out of frame to the north and east of the survey region for this project, but the interaction of the Monoceros loop SNR and the Rosette nebula has historically been somewhat unclear. It was generally thought that the SNR is more distant than the nebula itself, and excitation from the loop may be the source of the high electron temperature in the northern nebula [106]. The SNR appears to cause filamentary contributions to the optical emission of the nebula where they overlap [24], but there is no significant attenuation of the TeV gamma ray emission of the SNR itself in the region of potential interaction [3]. Recent studies using results from NASA’s Fermi Gamma-ray Space Telescope have shown that gamma ray emission in the loop is in fact most intense where the loop interacts with the Rosette nebula [74]. The north eastern portion of the Rosette Nebula appears to be irradiated by cosmic rays from the SNR, and Katagiri et. al. propose that the interaction between these cosmic rays and the matter within the nebula acts to produce gamma rays and may create significant inhomogeneities in the gas [74]. Consequently, this interaction may account for some of the filamentary shock structures visible in this region of the nebula, as discussed later.

Because of the optical nebula’s considerable size and relative proximity, it has been a well studied region of space. However, its considerable scale has proven to be problematic as observations have been limited to specific details of the nebula. A holistic view of the structure is not possible with large instruments due to field of view restrictions. Consequently, what is known of the Rosette Nebula is a litany of small scale, highly detailed observations that have not as yet been assembled into a complete picture of the physical processes of this unique object.
Figure 1.1: A false color view of the Rosette nebula composited from imagery collected during this project. The standard Hubble color scheme is used, with red [SII] emission, green Hα, and blue [OIII] emission. All filters are square root scaled, and relative flux from [OIII] and [SII] has been enhanced for clarity.
Figure 1.2: A nearly true color view of the Rosette nebula assembled from project data shown on a square root scale. Hα is shown in red, [OIII] in green, and Hβ in blue. Region A: SNR region of potential interaction, Region B: Elephant trunks and globulettes, Region C: Central cluster and bubble, Region D: South western PDR, Region E: South eastern ridge and molecular cloud.
1.2 HII Regions

HII regions like the Rosette are large gaseous clouds whose dynamics are driven by hot, ionizing central stars. The nebula is a “blister” of ionized gas formed out of the substance of the larger cloud of molecular gas and dust.

The cold molecular cloud is composed primarily of hydrogen, along with a mixture of heavier trace gases. These regions are also populated by silicate dust formed in the atmospheres of cooling stars, and often contain a complex population of polycyclic hydrocarbons \[168\]. Cold dust provides a favorable environment for the formation of hydrogen molecules (H\(_2\)). Density fluctuations within the cloud will eventually lead to gravitational collapse and star formation, creating an initial generation of stars. Stars with a surface temperature in excess of 20,000 K (stellar type B0 and above) produce some ultraviolet photons with energies in excess of 13.6 eV, sufficient to ionize hydrogen. The resulting supply of ionizing photons ionizes a volume of the hydrogen gas, creating the nebula. Recombination of protons and electrons into atomic hydrogen is responsible for the bulk of photon emission from these regions. In particular, ionized electrons recombining to the n = 2 level are responsible for hydrogen alpha (red) and hydrogen beta (aquamarine) lines which combine to create the characteristic rose hue seen in optical images of these regions \[71\].

One of the defining physical processes of HII regions is the equilibrium between ionization and recombination within the gas. For clarity, it is useful to consider the case of a single ionizing star in a cloud of pure, uniform hydrogen gas. The ionization equilibrium can then be expressed by equation

\[
n(H^0) \int_{\nu_0}^{\infty} \frac{4\pi J_{\nu} a_{\nu}(H^0)}{h\nu} d\nu = n(H^0) \int_{\nu_0}^{\infty} \phi_{\nu} a_{\nu}(H^0) d\nu \\
= n(H^0) \Gamma(H^0) = n_e n_p \alpha(H^0, T).
\]

Here, \(n(H^0)\), \(n_e\), and \(n_p\) are the density per unit volume of the neutral atom, electron, and proton respectively, while \(\alpha(H^0, T)\) is the recombination coefficient \[44\]. Therefore, the right-hand side of the equation gives the number of recombinations per unit volume per unit time. At equilibrium, this recombination rate will be equal to the rate of ionization per unit time, shown on the left-hand side of the expression. There, \(J_{\nu}\) is the mean intensity of radiation in energy units per unit area, per unit time, per unit solid angle, per unit frequency interval and therefore \(\phi_{\nu} = 4\pi J_{\nu}/h\nu\) is the incident photons per unit area, per unit time, per unit frequency interval. The threshold energy for ionization is \(h\nu_0\) (13.6 eV) and therefore \(\nu_0\) is the threshold frequency for an ionizing photon \((3.29 \times 10^{15}\) Hz\). The quantity \(a_{\nu}(H^0)\) is the ionization cross section for hydrogen by photons above the threshold energy, and consequently the integral product \(\Gamma(H^0)\) gives the number of photoionizations per atom per unit time, as expected \[44\].

The ultraviolet radiation throughout the volume of the nebula is sufficiently intense that hydrogen is almost completely ionized, excepting a very thin shell of warm atomic hydrogen at the outer boundary of the ionized region (referred to as an HI...
The field is also sufficiently energetic that to good approximation all ionization is from the ground state of the hydrogen atom, with that ionization rate being balanced by the recombination rate to all levels of the hydrogen atom \[47\].

In the idealized case of a single ionizing star in a uniform hydrogen cloud, the uniform emission of ionizing radiation in all directions results in a spherical HII region known as a Strömgren Sphere. Photons in this environment have relatively short mean free paths, ensuring absorption at short distances from their point of emission. Therefore, the radius of this sphere \(R_S\) depends only on the electron density \(n_e\), proton density \(n_p\), the recombination coefficient of hydrogen minus the ground state \(\alpha_B\), and the number of ionizing photons per second being emitted by the central star \(N_{UV}\) \[44\]. The ionizing photon rate is simply a function of the luminosity of the star \(L_\nu\), so we find

\[
\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu = N_{UV} = \left(\frac{4\pi}{3}\right) R_S^3 n_e n_p \alpha_B.
\]

Real nebulae like the Rosette are clumpy and complex, containing density variations, dust, heavier elements with higher ionization thresholds, and multiple ionizing sources. The resulting structure, however, must still follow the essential physics outlined here. An ionization equilibrium must be established and maintained within the object \[44\].

1.3 Central Cluster

NGC 2244, the young cluster apparently centered within the Rosette, contains the massive OB stars which are the driving force behind the dynamics of the nebula itself. The O stars and super heated surrounding gas within the nebula generate intense x-ray and ultraviolet emission which has a profound effect on every object in the region \[11\]. The brightest stars of NGC 2244 have consequently served as the principle diagnostics of the age, distance, and other vital statistics of the nebula. Note that while a large number of NGC 2244 members occupy the central cavity of the Rosette, many identified members exist significantly further from the center of the optical nebula.

The main cluster’s apparent center (based on stellar density distribution) is right ascension 06h 31m 59.9s, declination 04° 55′ 36″ \[86\]. It is spherical in shape with a 24′ angular diameter \[112\]. Due to the orientation of the Rosette cavity with respect to line of sight, it is difficult to distinguish cluster members from field stars. As a consequence, estimates of total cluster membership vary considerably. Optical regime studies prior to the mid-2000’s frequently resulted in cluster membership Figures of around 100, specifically 92 from Sabogal-Martinez et al. in 2001 \[135\] and 103 from Higuera et al. in 2002 \[67\]. More recent studies in the infrared have resulted in much larger numbers due to the volume of pre-main sequence stars detected and ascribed to the cluster. For example, in a study based on 2MASS data J. Z. Li estimated 1005 cluster members \[86\]. Regardless, the principle disagreement is with regards to the lower mass stars. There is high confidence that the cluster contains at least 30 O
Figure 1.3: A zoomed Hα image of the central cavity of the Rosette Nebula with the six O-type members of NGC 2244 highlighted. These stars, and especially the two hottest members (HD 46223 and 46150) drive the ionization that creates the visible nebula. Stellar identifications from Simbad [23].

and B type stars, and these are the engine which drive the surrounding nebula [112]. These 30 include six O class stars, highlighted in Figure 1.3 [62] [95]. Most recent population surveys of this cluster have shown a flat initial mass function around \( \gamma = -0.7 \) [65] and a high velocity dispersion, \( \sigma = 35 \text{ km/s} \). It is consequently expected that NGC 2244 is not gravitationally stable and will, in a time span on the order of \( 10^7 \) years, fly apart [28] [13].

The distance to the Rosette nebula has historically been given as 1400-1700 pc in most literature, based on studies of cluster stars and a reasonable assumption of coplanarity with the gas [28]. The uncertainty in this range is due to the fact that the object is beyond parallax range, and spectroscopic and photometric means of distance determination rely on a clear understanding of foreground and local extinction. Consequently, the unknown degree of extinction and reddening toward the central cavity of the nebula presents a significant problem for any distance estimate. While it is widely accepted that the local extinction should be quite low due to the appar-
ent excavation of the central cavity, there is still significant dispute about the exact values. Extinction estimates based on 2MASS studies show a mean visual extinction of $A_V$ 1.5 mag within a 10' radius of the cluster center [80] and the equivalent mean reddening figure determined from study of the 28 optically brightest cluster members is $E(B-V) = 0.47$. A survey of extinction and reddening measurements throughout the literature shows these to be representative of the mean [13]. The same study concluded that a standard reddening law appears to fit cluster observations, with a total to selective extinction ratio of $R_V = 3.1$, typical for pointings within the Milky Way [65].

Even with these values widely accepted, different methods frequently return significantly different distance estimates to the cluster. A study of cluster star V578 Mon, an eclipsing binary in NGC 2244 by Hensberge et al. in 2000 assigned a distance of 1.39 kpc. They utilized a Fourier disentangling technique to parse out the individual components of the spectrum and analyze the temperature of each. A UBVI and H-alpha photometric study of the 14 pre-main sequence stars and seven pre-main sequence candidates by Park and Sung (2002) resulted in a distance calculation of 1.7 kpc [112]. Recent studies of the nebula and cluster have often adopted one or the other of these values, or simply averaged the two. Clearly, substantial uncertainty still exists [28][95].

This distance uncertainty is likely to be resolved once the full data release from the European Space Agency’s Gaia mission becomes available. Gaia, launched in late 2013, is a space-based instrument specifically built for high precision parallax measurements of stars in the Milky Way. Consequently it will provide a high precision distance measurement to NGC 2244 which will inform future Rosette distance estimates. The first data release was in September of 2016, and shows a mean distance to the O stars in the cluster of approximately 1.2 kpc. This is roughly 20% closer than previous distance measurements, and if accurate would have an enormous impact on our understanding of the physical size of the nebula. The first data release, however, has significant limitations. Parallax uncertainties were in the range of 0.2 milli-arcseconds, corresponding to distance uncertainties on the order of ±100 pc at the distance cited for the cluster [99]. Nevertheless, it seems likely from this data that the cluster, and therefore the nebula, are closer than previously believed. The second data release, anticipated in April 2018, should provide a higher precision distance estimate as well as insight into the geometry of the cluster itself [50].

The age of the cluster had long been taken to be 4 Myr for the main sequence turn off, as summarized in Perez et al. (1989) [115]. More recent estimates have tended to point to a younger age, and the aforementioned analysis of V578 Mons in Hensberge et al. (2000) appears to indicate that this binary is in fact 2.3 Myr old [65]. Subsequent studies have attempted to reconcile this wide disparity in cluster age estimates with limited success. This discrepancy also appears in studies of the outward expansion of the HI shell surrounding the nebula. Kuchar and Bania (1993) found that this neutral shell was travelling radially away from the center of the cluster at 4.5 km/s, evidencing an overall dynamical age of 4 Myr for the nebula itself [81]. More recent studies, such as those by Imara et al. (2011) have estimated the rate of expansion of this shell at 13 - 14 km/s, implying a younger cluster age [70]. Since
the central cluster is driving the expansion and ionization of this gas, an ionizing star must have been present to begin this process. Berghöfer and Christian (2002) observed in a large scale optical photometric survey of X-ray selected stars that while most cluster stars show an apparent age up to 3 Myr, a population of younger, lower mass stars also exists as well. This appears to be an indication of recent or ongoing star formation [8]. Park and Sung also demonstrated through UBVI and H-α photometry that, while the main sequence turn off age of cluster members is 1.9 Myr, the pre-main sequence ages show a 6 Myr spread. They proposed that as many as 45% of cluster members may be older than 3 Myr [112]. This is taken to be evidence of an earlier star forming episode in the history of the cluster [28].

Confusion surrounding the cluster’s age is further compounded by recent studies of the young interstellar bubble at the center of the nebula. A 2010 study of IUE data by Bruhweiler et. al. found that the central cavity is expanding outward at 56 km/s with respect to the embedded OB cluster stars, in contrast to the 13 km/s expansion of the HII gas itself. This implies that the cavity is much younger than the cluster stars themselves, having an age on the order of 10^4 years. Formation mechanisms for this bubble are still contested [16]. Furthermore, studies of the magnetic field within the Rosette suggest that NGC 2244 has a profound impact on the polarization of the region, creating significant deviation from the ambient galactic magnetic field [138].

The cluster emits richly in UV and x-rays, and at least one of the young member stars has an unusually massive magnetic field [4]. It is richly populated by pre-main sequence stars[63], and two of the brightest O type stars exhibit HeII and HeI lines which were the first observed in stars of this type [36]. X-ray studies evidence that many stars in the cluster are of the T Tauri variety [29].

In addition to over 300 stellar sources, the central cavity of the Rosette nebula also emits diffuse soft x-ray emission consistent with extraordinarily hot 10 MK gas in the region. This is likely a product of fast stellar winds from the O stars interacting with the surrounding medium [158].

The three dimensional geometry of both the cluster and the surrounding gas is also an open question. One study suggested that the apparently cylindrical shape of the central cavity may be a consequence of NGC 2244 actually being a twin cluster, containing a "satellite" group is located 6.6pc west of the center of the main cluster. This satellite cluster would be responsible for a hot outflow of gases from the central cavity using a “punctured bubble” model [86]. Other studies have proposed a classic spherical construction for the nebula [124], or a sphere with a hollow cavity at its center [16]. It is certainly the case that the geometry of the nebula and that of the cluster are inextricably tied, and that by understanding one we may better understand the other.

1.4 Dust and Mid IR Emission

The Rosette Nebula is a dusty object, and this dust acts as a tracer to many of its most significant features. A complete understanding of its distribution, then, is vital to understanding the processes of the nebula as a whole. Early investigation of the nebula evidenced an electron temperature gradient across the region, from
8000K in the north west to 5000K in the south east. This was thought, and has been subsequently confirmed, to be an indicator that the south eastern nebula is dustier [40]. The IRAS experiment, which has motivated most of the subsequent infrared study of the Rosette nebula, observed mid IR emission in various bands. The Midcourse Space Experiment followed up those observations in higher resolution across many of the same bands, and provided tantalizing glimpses of nebula dynamics prior to the modern flourishing of infrared imaging and spectroscopy [79]. WISE has provided higher sensitivity, higher resolution imagery at the shorter wavelengths [170]. The Japanese Akari mission has provided higher resolution long wavelength data for the entire nebula [153]. Spitzer and Herschel observations have only covered isolated regions of the Rosette nebula, due to the scale of the object, limitations to their field of view, and of course limitations on observing time [72] [141].

Both IRAS and Midcourse observed the nebula in 12, 25, 60, and 100 $\mu$m radiation. It has long been thought that the 12$\mu$m emission is due to small dust particles [37]. However, the 12 $\mu$m IRAS data does not appear to show dust temperature following the expected heating gradient. This, it is proposed, is because the emitting particles are destroyed by ionizing radiation from the central cluster. At least some emission in this band is a result of polycyclic aromatic hydrocarbons (PAH’s), complex organic molecules which would be destroyed by the intense radiation field [168]. Recent observations have verified that emission in this band is very weak within the cavity of the optical nebula compared to its strength in the outer ring, and that this distribution matches the expected heating gradient if emitter destruction is taken into account [79]. Large grain dust, similarly, is indicated by the 60 and 100 $\mu$m emission within the nebula and since these larger grains are not so easily destroyed, this infrared light is distributed as would be expected by thermal heating from the central stars throughout the nebula [79].

The 25 $\mu$m emission proves to be a somewhat more complex problem. It shows a strong peak at both the ionization edge and the edge of the inner cavity, but a steep decline in the HII region between. In fact, this behavior is seen in both the Midcourse Space Experiment D and E emission bands [79]. Earlier research had concluded that this component of the Rosette’s mid infrared light was due to [OIV] lines, but it has been demonstrated that this could only account for 66% of the observed emission of this type [146]. It is now suspected that only planetary nebulae have significant [OIV] emission, making this explanation all the more problematic. Equilibrium heated dust particles do not appear to attain the necessary temperatures to explain this emission, though it has been proposed that exploration of transient heating effects may provide a clue. At present, however, no satisfactory explanation for the distribution of this radiation within the Rosette nebula exists [79].

Mid-IR emission is markedly more intense in the southern Rosette nebula due to photon dissociated regions, in large part those on the surface of the clump structures discussed below [79]. The Rosette Molecular Complex is dotted with several excited regions, which are thought to be driven by young stellar objects [172].
1.5 The Rosette Molecular Complex

The Rosette molecular complex (RMC) is a massive cloud of molecular and neutral atomic hydrogen, accompanied by a coincident cloud of interstellar dust. The Rosette nebula is an ionized blister on the north western tip of this cloud. The densest portion of the cloud lies to the nebula’s south east and the entire cloud evidences a sharp, well defined boundary with the surrounding space [12]. The total kinetic energy of the nebula’s expansion into the surrounding atomic shell is $3.8 \times 10^{48}$ ergs, which is 2% of the total energy available to the central cluster [81].

The RMC is estimated to contain $1.3 \times 10^5$ solar masses of molecular hydrogen. This molecular material is surrounded by an equivalent mass of atomic hydrogen [12]. This is accompanied by 11000 solar masses of dust. Along with stars and the nebula itself, the total mass of the complex has been estimated at $3.26 \times 10^5$ solar masses, but this estimate pre-dates the discovery of many occluded embedded clusters. The entire
complex may be rotating, with the south east showing a negative velocity component and the north west a positive velocity component with respect to the 14.3 km/s mean radial velocity for the entire complex observed by Celnik (1986) [26]. In that work, the center of rotation appeared to reside at right ascension 6h 30m 35s, declination 4° 22′, somewhat south and east of the visible nebula [26]. However, higher resolution studies have drawn these conclusions into doubt. The molecular cloud is highly turbulent, and attempts to disentangle rotational and turbulent velocity components have produced divergent results. After a recent detailed HI survey, Imara et. al (2011) proposed that the cloud may not be rotating at all [70].

The Rosette molecular complex, like all molecular cloud complexes, is highly inhomogeneous. It is populated by knots of material, or clumps, which are concentrations of dust and gas ten times denser than the surrounding material [11]. Over 2000 such compact gas clumps have been documented in the region [39]. These clumps exhibit kinetic temperatures from 15-20K [51]. The molecular cloud is “clumpy” down to a scale of 0.1 pc, and this clumpiness is self similar across a broad range of mass and spatial scales. Clumps vary in mass from 5 to 1743 solar masses [142], and only the most massive clumps (8% of the total population) tend to be gravitationally bound. Many other clumps are pressure bound; trapped between density layers in the ridges between the expanding HII region and the denser molecular cloud [88]. These tend to have much higher speed spectral components, and many exhibit Herbig Haro characteristics indicating active star formation [97].

Modern studies of the RMC agree that the motion of bulk molecular gas is principally driven by expansion of the cloud away from the O stars [39] [70]. More massive clumps have a lower velocity dispersion and tend towards the mid plane, implying a dynamically evolved system that has not yet reached energy equipartition. [169]. Several of the high speed knot-like clumps appear to have blue shifted filamentary material connected to or near them [30], and evidence of bow shocking and excitation [31]. The pervasive UV flux emanating from the central cluster creates photon dissociated regions on the surface of the clumps, which emit a weak [CII] 158µm emission. The depth of penetration of UV radiation into the cloud structure implies a density disparity on the order of $10^2$. Gas mapped by CO emission in the complex shows a mean density of $10^5$ cm$^{-3}$, whereas areas of [CII] emission have a density on the order of $10^4$ cm$^{-3}$ [143]. The surface temperature of the clumps, estimated from changes in the $J = 3-2/1-0$ $^{12}$CO line ratio, appears to decrease steadily with radial distance from the central O stars of NGC 2244 [39].

There are a number of molecular outflows throughout the complex, apparent in CO emission and, in many cases, also bright in [SII] emission [172]. A total of seven such parsec scale molecular outflows have been confirmed to date, with several other possible detections [39]. Most of these exist along the south east boundary between the nebula and larger molecular cloud, and can be observed in the filamentary structures in that region in our own project data. These boundary outflows appear to correlate with areas of active star formation, and appear to be driven by a young stellar objects (YSO’s) embedded in the pressure layers between the cloud and nebula [117].

In addition to the Rosette, two other emission nebulae are associated with the
RMC. These are Sh 2-280 (LBN 970), located at right ascension 6h 34m 22s and declination +2° 28′ 06″ [45], and Sh 2-282 (LBN 978), located at right ascension 6h 38m 08s and declination +1° 25′ 12″ [45]. Both are far to the south of the Rosette nebula, and they do not appear in our project data.

1.6 Star Formation

The Rosette complex is a very active star forming region, part of the larger Mons OB-2 massive star forming association, and it is within the clumps of dust and gas previously discussed that this star formation occurs. Studies have consistently found that roughly 20 % of the total clump population is protostellar [41].

AFGL 961 was the first observed protostar in the complex, embedded in the south eastern interface region between the Rosette nebula and molecular cloud. It was discovered in 1973 [32], and is prominent in infrared imagery. With modern infrared imaging, including recent Herschel studies, it has become clear that the Rosette complex is home to at least 4000 young stellar objects distributed across a total of 13 clusters [17].

Star forming occurs most frequently in the ionization pressure bound clumps near the nebula, and it is widely thought that the emission characteristics of this environment may stimulate the process [169]. Emission from the central cluster is likely not the sole motivator for star formation, however, as evidenced by the emergence of several clusters of young stellar objects inside the deep cloud [116]. The size of clusters appears to be anticorrelated to IR excess and mean extinction, implying that newly formed clusters start out as compact objects and then expand. A FLAMINGOS census of the RMC revealed that young clusters contain 60% of the total stellar population of the complex and 86% of the stellar population of the cloud itself [133].

Intensive studies by Li et. al. in the mid 2000’s using 2MASS near infrared data showed ages for two medium mass clusters on the order of 1 Myr. Both clusters were in the south eastern region between the nebula and cloud, and were determined to be embedded in an arc or fragmented shell of atomic hydrogen. Candidate member stars from these clusters are evenly distributed across the compression layers in the region. They appear to be gravitationally unbound, and Li et. al. proposed that expanding pressure shells are impeding the harshest ionizing radiation from the central cluster from encroaching into the cloud and disrupting star forming behavior there [88].

These clusters, and many others, are thought to be a product of “multi-seeded” star formation throughout the region. Newly formed stars are driving the formation of more new stars and consequently star formation appears to be occurring both in serial and parallel. All detected new clusters are medium to high mass, and their formation appears to follow tracks laid out by macroturbulence in the surrounding material. [87] The Li group observed that star formation is not confined to the ionization front of the nebula but rather can also be directly related to other ionizing objects. Specifically, a study was conducted on one dense cluster located just south of AFGL 961. Star formation here appears to be driven by the binary and other newly hatched stars in the region, supporting the idea of sequential star formation in the complex [89]. Density mapping of the molecular cloud supports the idea of
macroturbulence as a strong factor in cluster formation. The densest portions of the molecular cloud have a filamentary structure, with most new star formation occurring at the filament junctions [140].

FLAMINGOS observations have also provided evidence of sequential star formation. The age of young clusters can be mapped not only by their degree of compactness, but also by the extent of circumstellar IR emission present. FLAMINGOS observed evidence of star formation in four distinct zones of the complex, and was able to directly correlate each region against the age of the clusters therein [133]. The first is the oldest region of star formation, the nebula itself. Younger than these are the stars present in the ridge of the nebula itself, near the ionization front. Younger still are the stars in the core of the molecular cloud, at the outermost reach of the HII region’s influence. Finally, the youngest star clusters are present in the reaches of the molecular complex furthest from the nebula. These last two groups evidence that the direct influence of the nebula and central cluster are not required to drive star formation, and make a strong case for the sequential driving hypothesis. The exact impact of HII regions on star formation is still not known [133].

Herschel observations of the cloud, however, have complicated this sequential picture considerably. Many newly discovered young stellar objects (YSO’s) in the deep cloud have ages which do not correspond to this sequential formation hypothesis, and indeed no simple model reliant upon the central cluster as the sole instigator of stimulated star formation in the RMC appears to fit the data [17]. A recent CHANDRA and Spitzer study even suggested that star formation across the complex appeared to have started at approximately the same time [171]. Clearly, the exact mechanics of massive star formation are still a subject of investigation, and observations of this behavior in the Rosette region have been fundamental to our evolving understanding of this phenomenon.

1.7 Elephant Trunks and Globulettes

Some optically dark structures in the region are not clumps as discussed above, but rather appear as long “elephant trunks.” These objects are concentrated in the north and north western portion of the nebula, and stand out sharply against the surrounding hydrogen emission in optical imagery. They appear to be embedded in the HII plasma and are strongly exposed to the harsh ionizing radiation of NGC 2244 [28]. These elephant trunk globules show a bright outline in CO radio observations. In this spectrum, a line shift consistent with outward motion buoyed by the cluster wind from NGC 2244 is observable. The elongation of these clumps, coupled with their line shift observed velocity, seems to indicate that they have been traveling outward from the center of the nebula since the central cluster was born approximately 4 Myr ago [144]. These “trunks” appear to be comprised of helical or serpentine dark filaments, and appear to be the broken remnants of molecular shells [91]. Looked at as a sinusoidal structure, these filaments have a wavelength roughly 7-9 times the radius of the trunk that houses them. The filaments evidence mean extinctions on the order of 0.5 to 1 mag, resulting in an estimated molecular hydrogen density of $10^4$ cm$^{-3}$. The helical structure of these filaments is apparently due to magnetic fields,
and it is believed that this may in turn result in electric currents along their lengths. This, in turn, aids to hold these structures together in the face of cluster wind and radiation [19].

Alongside the elephant trunks in the north western nebula are a collection of speck globules, or “globulettes.” These are small spherical or tear shaped pockets of dust and molecular material. They appear dark against the emission of the HII region, and are frequently located either attached to or in proximity to elephant trunk globules. They are believed to form through erosion of elephant trunks, and the combination of the intense photoionization in the Rosette and the profusion of trunk globules may explain their unusual abundance here. These structures are small compared to the star forming clumps discussed earlier. The average globulette has a radius of only 2.5 kAU, the largest are no greater than 10 kAU. They have masses of less than 13 $M_J$ [53].

A 2014 Spitzer study of one portion of the elephant trunk complex in the north western Rosette nebula found that these elephant trunk globules and their associated globulettes were bright in the 2.12 $\mu$m line of molecular $H_2$, evidencing $H_2$ number densities on the order of $10^{-4}$ cm$^{-3}$ or higher. In general, the structures were found to be surprisingly dense, and two NIR protostellar objects were discerned in one of the densest elephant trunk knots [91].

One particular trunk-like object, however, does not conform to the behavior of the others. This “rogue” elephant trunk is located near the center of the nebula, and is a source of 25 $\mu$m emission, unlike the larger elephant trunk complex where the IR emission is limited to the shorter 8 and 12 $\mu$m bands. It is also unusual in that its location is apparently antithetical to the elongation by outward motion explanation above. It seems to be too close to the center of the nebula to have survived this process, and it has been proposed by Kraemer et. al. (2003) that this may be an embedded feature well along the same line of sight as the nebula but outside the influence of the cluster wind. Alternatively, the cluster winds may not be isotropic and this globule may have escaped their influence and therefore not been dispersed [79]. Our own attempt to investigate this object is documented below.

The globulettes have been studied in optical and radio observation. They present optical extinctions of 1 to 3 mag, and emit clearly in $^{12}$CO, $^{13}$CO, and CS radio lines. These observations allow density estimates on the order of $10^4$ cm$^{-3}$, and lead to lifetime estimates in the face of stellar radiation pressure and ionization on the order of $10^4$ years [54]. These estimates, however, do not account for the impact of the surrounding hydrogen plasma. Recent studies have shown that these objects are in fact held together by radiation pressure, resulting in far greater lifetimes than originally expected. Consequently, rather than simply being blown apart like Herbig-Haro objects and other similar structures left unshielded, the limiting lifetime of globulettes becomes a consequence of the encroachment of ultraviolet flux into the interior of the globulette. Even in the Rosette’s harsh environment, this encroachment appears to occur on a time scale of 4 Myr, providing adequate time for these objects to collapse and form low mass planetary objects or, possibly, brown dwarf stars [53].

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Figure 1.5: An elephant trunk and surrounding globuletes, cropped from Hα project data. These dust structures are dark against the surrounding Hα emission.
Chapter 2 Observations

Primary optical data collection for wide field imagery was conducted from October 2008 until January 2010 at Moore Observatory in Brownsboro, KY. Spectral data were acquired during observing seasons from March 2010 until January 2011.

2.1 Instrumentation

A Takahashi FSQ-106ED f/4, apochromatic lens system was matched with an Apogee Alta U9000 CCD camera, an Optec IFW filter wheel, and a Paramount ME robotic tracking system to provide deep long exposure imaging of the Rosette region. The tracking and imaging components were operated using the observatory’s XmTel and XmCCD software that permit remote operation and partially automated data collection.

A set of narrow band filters, described in Table 2.1, were used to capture specific emission lines from target nebulae, and to suppress urban sky glow. The custom Hα filter is designed with a transmission profile to minimize contamination from [NII] lines that typically contaminate narrow band Hα images.

The Alta U9000 camera utilizes a Kodak KAF-0900 sensor (now manufactured by On Semiconductor) with 12 µm square pixels, a 75.3 dB dynamic range, and a peak quantum efficiency of 64%. When paired with the telescope optics, each 16-bit, 3054 × 3054 pixel wide field frame encompasses a 3.96 × 3.96 degree field with an image scale of 4.67 arcseconds per pixel, allowing the entire Rosette nebula environment to be imaged in a single frame.

The instrument was mounted on a robotically controlled German equatorial Paramount ME, creating a stable platform for 200 s exposures with only sub-pixel tracking errors.

Spectroscopic data were collected using WISPI (Wide-field Spectral Imager) [77], an instrument designed specifically to study the Rosette and other large ISM features. WISPI samples a 4° strip of sky along a single declination line, and acquires a spectrum from 400 to 800 nm for a “slice” of the sky in right ascension (i.e. east-west) across the entire Rosette Nebula. A 400 mm f/2.8 Nikor objective images an extended

Table 2.1: Wide field imaging narrow band filters.

<table>
<thead>
<tr>
<th>Filter Band</th>
<th>Center</th>
<th>FWHM</th>
<th>Peak Transmission</th>
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<td>75%</td>
</tr>
<tr>
<td>Hβ</td>
<td>486.1 nm</td>
<td>4.5 nm</td>
<td>87%</td>
</tr>
<tr>
<td>[OIII]</td>
<td>500.7 nm</td>
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<td>77%</td>
</tr>
<tr>
<td>[SII]</td>
<td>672.4 nm</td>
<td>4.5 nm</td>
<td>88%</td>
</tr>
</tbody>
</table>
Figure 2.1: The Takahashi FSQ 106ED at the beginning of data collection in October 2008.

Figure 2.2: Optical schematic of the Takahashi FSQ 106Ed
object on a long slit that is set to a width of 72 μm (which is roughly 3.5 pixels in the image plane). The light passing through the slit is collimated by a 180 mm f/2.8 Nikor lens system and illuminates a 300 groove/mm diffraction grating blazed for 762 nm in the first order. The resultant spectrum is imaged by a 200 mm f/2 Nikor lens system onto an Apogee U6 1024 × 1024, 24 × 24 μm pixel Peltier-cooled CCD sensor. The optical system provides a dispersion of 0.392 nm (3.92 Å) per pixel along the spectral axis, and samples 11.1 arcseconds per pixel along the spatial axis. The 200/180 magnification of the system results in an effective slit width of 64.8 μm at the focal point of the objective, and consequently an effective slit width of 33.4 arcseconds in declination on the sky.

The instrument is mounted on a precision robotic tracking system with a live video guider that allows the observer to point it a specific field and then offset precisely in a sequence of exposures. Under the XmTel control software, once the pointing for the first image is established, the tracking system provides a measurement of the offset for subsequent exposures. The long slit samples spatially resolved elements spanning 4° (16 minutes of time) in right ascension at constant declination. This allows rapid collection of flux data simultaneously from many spectral lines in well-defined slices across the target. Offset spectral images traverse the target in a raster and can be recombined during analysis to yield representative data volumes in which each element (voxel) is an area on the sky in which the spectrum is a third dimension.

2.2 Wide-field Database

The raw science imaging data collected during wide field observations are summarized in Table 2.2. In addition to the data listed, dark frames of the same exposure were collected during each night of observations, and averaged through a median filter in the ALSVID image processing suite to generate a master dark. On several clear mornings and evenings, short duration sky flats were taken, to allow correction of vignetting, pixel-to-pixel gain variations, and dust on optical elements. Although the imaging system exhibited long term stability that allowed use of dark and flat images acquired on many nights, during November of 2009 a frosting incident with the camera required it to be removed from the system and cleaned. New flat fields were acquired after that event and used for relevant data.

Flat field images were corrected for the camera’s dark and bias response by subtracting an averaged master dark for the same exposure time as the sky image. These dark-subtracted fields were then corrected for the twilight gradient which is non-negligible in wide field images. They were normalized and the entire set was processed with a median filter through the image stack to remove stars and produce a final, master flat for each filter for each of the two periods of observation (before and after November 2009).

Each science frame was then dark subtracted and flat fielded against their appropriate master flats to produce a base set of science frame data. At this stage the individual science images were spatially calibrated by processing with astrometry.net software, which performs a pattern matching routine to identified stars in the frames against a comprehensive database of stars with well defined positions.
Figure 2.3: A view of WISPI as it appeared in October 2008.
The software establishes the best representation of the image scale and orientation in the frame and attaches a World Coordinate System (WCS) with astrometric data to the header of each FITS file containing the original image data. The WCS header contains non-linear terms that accurately correct for small optical system distortions.

These processed individual frames were then visually inspected for cosmic rays, aircraft, meteor trails, clouds, or any other disruptive elements in the region of interest. Those frames found to be free of defects were organized into separate sets, and a straight co-added sum was produced of the valid data for each filter and target using SWARP software [9]. The software automatically aligns frames based on their WCS headers, interpolates between pixels using Lanczos resampling with $a = 4$, and produces a co-added mosaic that includes all regions of overlap. It adds an equivalent total exposure time to the header of the mosaic file, and transfers the WCS header as well as the original acquisition information so that the final data product contains a record of its origin. The resultant preliminary co-added mosaics are summarized in Table 2.3.
Table 2.2: Summary of collected wide field data. Each frame is one 200 second exposure. All frames have been dark subtracted, flat fielded, and have World Coordinate System (WCS) headers applied.

<table>
<thead>
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<th>Target</th>
<th>Filter</th>
<th>Collected Frames</th>
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<td>180</td>
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<tr>
<td>Rosette</td>
<td>H(\beta)</td>
<td>294</td>
</tr>
<tr>
<td>Rosette</td>
<td>[OIII]</td>
<td>192</td>
</tr>
<tr>
<td>Rosette</td>
<td>[SII]</td>
<td>145</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>H(\alpha)</td>
<td>102</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>H(\beta)</td>
<td>112</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>[OIII]</td>
<td>53</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>[SII]</td>
<td>62</td>
</tr>
<tr>
<td>M42</td>
<td>H(\alpha)</td>
<td>6</td>
</tr>
<tr>
<td>M42</td>
<td>H(\beta)</td>
<td>6</td>
</tr>
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<td>[OIII]</td>
<td>5</td>
</tr>
<tr>
<td>M42</td>
<td>[SII]</td>
<td>5</td>
</tr>
<tr>
<td>M17</td>
<td>H(\alpha)</td>
<td>11</td>
</tr>
<tr>
<td>M17</td>
<td>H(\beta)</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 2.5: The co-added H\(\alpha\) mosaic of the Rosette Nebula with a total exposure of 28,800 seconds (8 hours). It is shown on a square root flux scale to increase the dynamic range of the display.
Table 2.3: Table of wide field co-added mosaics and data products.

<table>
<thead>
<tr>
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<th>Type</th>
<th>Total Exposure (seconds)</th>
<th>Additional Processing</th>
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</thead>
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<td>Hα mosaic</td>
<td>28800</td>
<td>gradient removed, background subtracted</td>
</tr>
<tr>
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<td>Hβ mosaic</td>
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<tr>
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<td>[OIII] mosaic</td>
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<td>Rosette</td>
<td>[SII] mosaic</td>
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</tr>
<tr>
<td>NGC 7000</td>
<td>Hβ mosaic</td>
<td>10800</td>
<td>background subtracted</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>[OIII] mosaic</td>
<td>5000</td>
<td>background subtracted</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>[SII] mosaic</td>
<td>5000</td>
<td>background subtracted</td>
</tr>
<tr>
<td>M42</td>
<td>Hα mosaic</td>
<td>1200</td>
<td>gradient removed, background subtracted</td>
</tr>
<tr>
<td>M42</td>
<td>Hβ mosaic</td>
<td>1200</td>
<td>gradient removed, background subtracted</td>
</tr>
<tr>
<td>M42</td>
<td>[OIII] mosaic</td>
<td>1000</td>
<td>gradient removed, background subtracted</td>
</tr>
<tr>
<td>M42</td>
<td>[SII] mosaic</td>
<td>1000</td>
<td>gradient removed, background subtracted</td>
</tr>
</tbody>
</table>

Figure 2.6: The co-added Hα mosaic of the North American Nebula shown on a linear scale.
Sky light contributes both to a background signal and, due to the large angular area of the science frame, creates a readily visible gradient across the FSQ images. In the case of both the Rosette Nebula and M42, the object does not completely fill the frame, and it is therefore straightforward to select several regions with no nebular emission. Using ALSVID routines, a planar fit was applied to the background illumination and then subtracted, so as to remove the gradient effect. Second, a signal value was subtracted across the frame so as to set these regions to a signal value of zero. The effect was to remove all sky light contributions from the preliminary master frames. For NGC 7000, which is surrounded by regions rich in hydrogen emission, only two emission free regions were found. Consequently, no gradient removal was attempted, but a step removal to bring those regions to zero was completed as with the other objects.

SWARP was used to resample each of the four masters to the same pixel scale, locking the frame size at 4096 despite overlap regions. Each of the four masters was then hand aligned by reference to bright stars using the AstroImageJ package [34]. The final result was masters on all four filters which perfectly overlap at the pixel level.

The wide field image processing pipeline is summarized in Figure 2.7.

2.3 High Spatial Resolution Images

Observations of the northwest Rosette were taken with the Moore Observatory 0.52-meter corrected Dall-Kirkham telescope (CDK20N) on a 0.536 arcsec/pixel scale, providing dramatically greater spatial resolution than the wide field image database at the expense of a smaller field of view. The $0.61^\circ \times 0.61^\circ$ degree field of view was centered on a region rich in elephant trunk globules, distinctive helical dust structures whose extinction characteristics may aid in a better understanding of the three dimensional structure of this part of the nebula. Single exposures show magnitudes down to $18^{th}$.

100 second exposures were collected on BVRI bands, then dark subtracted and flat fielded. These images were then WCS calibrated using astrometry.net, and co-added with SWarp.

2.4 Spectral Images

The database of spectra acquired with WISPI is described in Table 2.4. As with the wide field data, dark frames of the same exposure time were collected on each night of observation, put through a median process, and used to subtract dark signal and camera bias from all science frames listed.

A spectral reference is also required to calibrate the wavelength and absolute flux in spectroscopic data of this kind. Several stars were observed, primarily in spring of 2010, to provide for this spectrometric calibration. An archive of hundreds of short exposure frames of data on the standard flux star Vega are in the database for use in this processing.
Figure 2.7: A flow chart showing the procedure used to process the FSQ data.
ALSVID routines allow us to sum along columns of a frame, and extract a spectrum at high signal-to-noise ratio from a limited range of right ascension along the sampled declination line. A representative co-added WISPI frame from the +4:51 declination line of Rosette is shown in Figure 2.9, and a spectrum extracted from this data is shown in Figures 2.10 and 2.11.

Subsequent evaluation of the data revealed a number of limiting factors in the collected spectra. Ultimately, a small subset of collected data from specific nights corresponding to the brightest portions of each nebula target were hand selected to avoid spectra impacted by poor focus or contaminated by high cirrus clouds or condensation/frosting. Stars visible in the WISPI frames were compared to the expected declination in the wide field images, allowing more precise identification of the slit location. This information, the known spatial scale on the detector, and the dispersion were used to create a WCS header identifying spatial coordinate in right ascension along the vertical axis and wavelength along the horizontal. Frames from nights and targets of interest were then hand-aligned and co-added using AstroImageJ software [33] to create a small subset of master frames for specific pointings on especially clear nights. Data used in the creation of these frames is summarized in Table 2.5.

Figure 2.8: A mosaic of B, V, R, and I filter images of the northwest Rosette Nebula taken with the CDK 20.
Table 2.4: Summary of WISPI spectroscopic data. All frames have been dark subtracted.

<table>
<thead>
<tr>
<th>Target</th>
<th>Target Declination</th>
<th>Exposures (100s)</th>
<th>Exposures (20s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosette</td>
<td>+04:31</td>
<td>97</td>
<td>0</td>
</tr>
<tr>
<td>Rosette</td>
<td>+04:41</td>
<td>95</td>
<td>0</td>
</tr>
<tr>
<td>Rosette</td>
<td>+04:51</td>
<td>117</td>
<td>0</td>
</tr>
<tr>
<td>Rosette</td>
<td>+05:01</td>
<td>104</td>
<td>0</td>
</tr>
<tr>
<td>Rosette</td>
<td>+05:11</td>
<td>87</td>
<td>0</td>
</tr>
<tr>
<td>Rosette</td>
<td>+05:21</td>
<td>86</td>
<td>0</td>
</tr>
<tr>
<td>Rosette</td>
<td>+05:31</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>+44:11</td>
<td>16</td>
<td>0</td>
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<tr>
<td>NGC 7000</td>
<td>+44:31</td>
<td>139</td>
<td>0</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>+44:51</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>M42</td>
<td>-05:14</td>
<td>0</td>
<td>28</td>
</tr>
<tr>
<td>M42</td>
<td>-05:19</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>M42</td>
<td>-05:24</td>
<td>19</td>
<td>91</td>
</tr>
<tr>
<td>M42</td>
<td>-05:29</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>M42</td>
<td>-05:34</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>M42</td>
<td>-05:39</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>M42</td>
<td>-05:44</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Vega</td>
<td>&gt; 100</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.5: Summary of final WISPI data products.

<table>
<thead>
<tr>
<th>Target</th>
<th>Actual Declination</th>
<th>Co-added Exposure Time (s)</th>
<th>Date of Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosette</td>
<td>+05:01</td>
<td>2000</td>
<td>Nov. 9, 2010</td>
</tr>
<tr>
<td>Rosette</td>
<td>+05:09</td>
<td>2000</td>
<td>Nov. 11, 2010</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>+44:28</td>
<td>1900</td>
<td>Nov. 8, 2010</td>
</tr>
<tr>
<td>M42</td>
<td>-05:39</td>
<td>1000</td>
<td>Nov. 9, 2010</td>
</tr>
</tbody>
</table>
Figure 2.9: A co-add of 20 WISPI spectral images of the +4:51 declination line of the Rosette nebula. The spatial dimension is vertical and covers about 2° in right ascension. The wavelength space is horizontal and spans from 800 nm on the left to 400 nm on the right. Hα is the structured line on the left, and the urban night sky sodium light makes the broad vertical feature in the center. A centered strip of this image was summed to produce Figures 2.10 and 2.11.
Figure 2.10: The long wavelength half of a sample spectrum collected from a region of the Rosette nebula along the +4:51 declination line. Identified peaks are labeled with wavelength in Angstroms (Å), and show both city light and nebula contributions. Note the strong Hα peak flanked by [NII] and [SII] from the Rosette.
Figure 2.11: The short wavelength half of the sample spectrum from Figure 2.10, showing notable nebula lines such as H$\beta$ and [OIII]. Na and Hg features are due to scattered urban light.
Atmospheric attenuation and reddening needed to be removed from the wide field frames before physical analysis of the results could begin. The goal was to translate from the actual accumulated exposure time on the ground to the effective exposure time at the top of the atmosphere (an air mass of zero). This process needed to be repeated for each filter and target.

3.1 Determining Extinction Per Air Mass

Due to Rayleigh scattering, atmospheric attenuation varies significantly at different wavelengths. Therefore, each of the four filter bands would correspond to a different attenuation per airmass. This relation would depend on a variety of factors specific to the observing location and had not previously been tested for observations at Moore Observatory, so it was necessary to derive an appropriate model for the effect of air mass at each of these filter wavelengths.

To this end, it was first necessary to determine the air mass through which each exposure was taken. Thanks to the extensive header on each wide field image, the date, time, and equatorial coordinates of each observation could be automatically retrieved. Coupled with the known location of observation, Python code was assembled to calculate the air mass of each frame and store that information in the image header. The conversion algorithms for date, time, and astronomical coordinates were adapted from convert.py routines by Adrian Price-Whelan at NYU [127]. The subsequent calculation of air mass was adapted from Sky Calculator by John Thorstensen of Dartmouth [155], and made use of a fourth order polynomial fit of airmass data from KPNO via Snell and Heiser [149].

Once the air mass for each observation had been calculated, a mechanism to compare signal attenuation from frame to frame (and air mass to air mass) was needed. A sample of stars was hand selected for this purpose, with care taken to ensure that signal from each star was strong in individual frames, but never saturated the detector. Circular regions around each target star were selected in SAOimage DS9 [148], the coordinates of these target stars and the region radius were output to a file, and a script written in Python to perform photometry on these targets. For each star, the script found the total signal within the region, and subtracted an averaged background from an annulus surrounding that region. To mitigate the impact of faint stars on the background signal, a second background average was taken neglecting any pixel more than two standard deviations from the average of the first pass.

For each individual image, the calculated air mass (retrieved from the header) and the signal from each star was recorded. In the end, if 15 stars were selected, the result was 15 separate data files, each a list of ordered pairs with air mass as the first value and signal from that star as the second. Consequently, the change in signal per airmass for each individual star could easily be observed. A relative magnitude ($m$)
Table 3.1: Magnitude change per air mass by filter, from Rosette photometric analysis.

<table>
<thead>
<tr>
<th>Filter Band</th>
<th>Average Slope (Magnitude per Air Mass)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>0.119563</td>
<td>0.008756</td>
</tr>
<tr>
<td>Hβ</td>
<td>0.307821</td>
<td>0.019256</td>
</tr>
<tr>
<td>[OIII]</td>
<td>0.191041</td>
<td>0.034115</td>
</tr>
<tr>
<td>[SII]</td>
<td>0.042806</td>
<td>0.013232</td>
</tr>
</tbody>
</table>

was then calculated from the raw signal \( (s) \) each data point using the relation

\[
m = -2.5 \log(s).
\]

(3.1)

Plotting the results for any star, the change in relative magnitude per airmass was found to be roughly linear, as expected. Because the Rosette Nebula was the primary object of study, it was decided that a magnitude extinction rule would be derived from the Rosette results, then applied as a check to the NGC 7000 and M42 observations. For each test star in the Rosette field on the Hα filter, the air mass and magnitude pairs were plotted and a linear regression was performed. To limit the impact of other extinction effects, such as cirrus clouds, outlier frames (those for which all stars deviated more than two standard deviations from the line of best fit) were removed and the regression was performed again. The resulting slopes are shown in Figure 3.1. Note that each star has a different offset, and these offsets were subtracted off for ease of visualization in the Figure.

This process was repeated on the Rosette data for each of the four filters, and statistics were collected for the resulting slopes. The resulting magnitude change per air mass was used in accounting for air mass effects for all FSQ data. The results are summarized in Table 3.1.

### 3.2 Effective Exposure Time Calculation

Generation of an effective exposure time at air mass zero involved a series of layered adjustments to the exposure time from the ground. The basic assumption of this analysis is that, if atmospheric effects have been properly accounted for, the test stars should have roughly constant magnitude from exposure to exposure. Python code was written to apply an algorithm which would generate an effective exposure time for each pairing of object and filter utilizing test star magnitude changes as the point of reference. For the Rosette, the starting point was simply the air mass and relative magnitude ordered pairs already generated in the previous process. For the other objects (M42 and NGC 7000) that same process was run to determine air mass and record test star relative magnitudes, but no slope fitting was done. The
Figure 3.1: A plot of all photometrically determined relative magnitudes (higher values are dimmer) for stars in the Rosette Hα data set vs. air mass at observation. Offsets subtracted for clarity of visualization. Points of a set color are all from the same star, observed at different times. Linear regressions for all stars are shown. Slopes are very similar, evidencing the dominant effect of air mass on atmospheric extinction. Note some vertical groups of different colors offset from the larger mass. These correspond to outlier observations with higher than typical extinction, possibly due to light clouds or other attenuating interference in that exposure.
change in magnitude per air mass for each filter from the Rosette results was instead used for all three objects, since these values should depend only on the atmospheric conditions above Moore Observatory. It was found that the slopes in Table 3.1 do in fact remove the air mass dependence from the recorded stellar relative magnitudes for the NGC 7000 and M42 data as well, supporting the claim that these slopes properly characterize the atmospheric reddening at the Moore Observatory site.

To determine what further exposure time adjustment was needed, the slope multiplied by air mass was then subtracted from the air mass and relative magnitude pairs. If air mass were the only thing impacting the relative magnitude of the test stars, this process would result in stars of constant magnitude at all air masses. The result is somewhat close to this ideal, the air mass dependence is clearly removed from the relative magnitude of the test stars, but there are still a limited number of frames which show a greater magnitude (and therefore greater extinction) than the median for all test stars. These frames were primarily from specific observing nights when the transparency was somewhat worse than the ideal. To account for this effect without removing useful data from the final mosaic, a night-by-night magnitude offset was determined. To do this, first the frames are sorted by night of observation. Next, a median air-mass corrected relative magnitude is determined for each star. The lowest median value night is the night with the lowest extinction, and is used as a reference floor. Each night then has its average magnitude difference from the floor calculated and stored as the offset for that night. The effective exposure time can then be calculated from the relation

\[ T = T_g \times 10^{-2/5(\text{m} \cdot x + N)}, \]  

(3.2)

where \( T \) is the effective exposure time at air mass zero, \( T_g \) is the exposure time at the ground, \( m \) is the calculated slope (magnitude change per air mass), \( x \) is the air mass of the observation, and \( N \) is the offset for the night of observation. For most object/filter pairings this process was sufficient to account for frame by frame magnitude variations, and resulted in constant relative magnitudes from frame to frame for a given star as expected. The calculated effective exposure time for each frame was determined, and the total for all frames of a given object/filter pairing was calculated and added to the header of the preliminary master mosaic.

However, in a few cases, a small number of individual observations (single frames) showed high magnitude (high extinction) even after accounting for air mass and nightly variation. These are cases where clouding or other short term effects temporarily attenuated the collected light. In the interest of retaining any and all useful data, an algorithm and accompanying Python code was generated to account for these few remaining outlier frames, which comprised less than 3% of total FSQ science frames collected. The majority of those frames came from a single night of Rosette Hα observations which suffered from intermittent, highly variable interference by high cirrus clouds.

Outlier frames were identified by taking an per-frame average across all stars and identifying those frames where, even with previous offsets, the average relative magnitude for all stars in that frame was still several standard deviations above the mean.
Table 3.2: Summary of calculated effective exposure times at air mass zero (the top of the atmosphere), along with outlier frame counts.

<table>
<thead>
<tr>
<th>Target</th>
<th>Filter</th>
<th>Effective Exposure Time (s)</th>
<th>Outlier Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosette</td>
<td>Hα</td>
<td>21665</td>
<td>20</td>
</tr>
<tr>
<td>Rosette</td>
<td>Hβ</td>
<td>26425</td>
<td>0</td>
</tr>
<tr>
<td>Rosette</td>
<td>[OIII]</td>
<td>21144</td>
<td>1</td>
</tr>
<tr>
<td>Rosette</td>
<td>[SII]</td>
<td>15973</td>
<td>0</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>Hα</td>
<td>13542</td>
<td>3</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>Hβ</td>
<td>7076</td>
<td>1</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>[OIII]</td>
<td>3816</td>
<td>0</td>
</tr>
<tr>
<td>NGC 7000</td>
<td>[SII]</td>
<td>4935</td>
<td>0</td>
</tr>
<tr>
<td>M42</td>
<td>Hα</td>
<td>1029</td>
<td>0</td>
</tr>
<tr>
<td>M42</td>
<td>Hβ</td>
<td>588</td>
<td>0</td>
</tr>
<tr>
<td>M42</td>
<td>[OIII]</td>
<td>740</td>
<td>0</td>
</tr>
<tr>
<td>M42</td>
<td>[SII]</td>
<td>940</td>
<td>0</td>
</tr>
</tbody>
</table>

from all frames. For frames identified as outliers, this magnitude difference above mean \((D)\) was added to the previously calculated offset. The resulting calculation for effective exposure time at the top of the atmosphere simply became

\[
T = T_g \times 10^{-2/5(m-x+N+D)}.
\]

(3.3)

Again, per frame effective exposure times for each object/filter pairing were then summed and the total was added to the header for the corresponding co-added master. Final effective exposure times with outlier counts are recorded for each filter and object combination in Table 3.2. The success of this method is illustrated in Figure 3.2 which shows the NGC 7000 Hα measurements after compensation for air mass and other extinction effects. As desired, the resulting stellar magnitudes are roughly constant from frame to frame, night to night, and independent of air mass. Note that the magnitude intercept for each star has been subtracted off in this graphic so that all stars can be presented overlaid in the same coordinate space.

### 3.3 WISPI Calibration

Spectral calibration of WISPI data was based on comparison to the absolute calibration of Vega (Alpha Lyrae) by Tüg and White [159]. Of the many frames available, the observation with greatest signal to noise was selected to serve as the observed spectrum for this calibration. The relevant portion of this dark subtracted science frame is shown in Figure 3.3.
Figure 3.2: A plot of all photometrically determined relative magnitudes for stars in the NGC 7000 Hα data set vs. air mass after compensation for air mass, night by night extinction, and individual frame variation. Again, the magnitude intercept for each star has been subtracted to allow easy comparison.

This two second exposure contained faint skylight contamination, like all collected WISPI data. Significant effort was made to determine the best mechanism by which to remove background light and sky lines (such as Na and Hg lines from street lights) from WISPI spectra. Observations showed that individual city light lines and background continuum varied over the course of any given night, from night to night, and from season to season. Ultimately, it was decided that subtraction of local background in each image was the only viable approach.

In the case of the Vega spectrum, pixel rows directly above and below the star were summed to create a background estimate. The star itself was then summed column by column and the background weighted and subtracted. The resulting spectrum is shown in black in Figure 3.6, prior to any further manipulation.

An unanticipated complication in reducing the WISPI measurements arose due to a variability in the focus quality dependent upon wavelength. A vertically zoomed image of the same Vega spectrum from Figure 3.6 is provided in Figure 3.5 to illustrate the issue. For a point source like Vega, soft focus at some wavelengths extends the
object into a disc. With WISPI’s narrow aperture slit, the result is that for softly focused portions of the spectrum, only a portion of the disc is sampled, and therefore only a portion of the incident light is detected. Fortunately, the distribution of light over the disc appears to be flat, rather than Gaussian, affording an opportunity for a geometric correction. The diameter variation was measured by carefully mapping the upper and lower bounds of the signal in Figure 3.5, then fitting the diameter variation with a nine parameter function of the form

\[ y = a_0 + a_1 e^{-\frac{x}{a_2}} + a_3 x^2 + a_4 x^4 + a_5 x^6 + a_6 x^8 + a_7 x^3 + a_8 x^5 \]  

(3.4)

where the subscripted \( a \)'s are the fitting parameters. The fractional light lost due to the slit cutting off portions of the extended light circle can then be determined from this fitted curve. Simply, the fractional light lost will be the area of the two cords on opposite sides of the slit. Assuming the star is centered on the slit, an assumption supported strongly by strong signal to noise ratio of the spectrum selected for this process, then the fractional light lost \( f \) as a function of the slit width \( w \) and defocus diameter \( d \) is given by:

\[ f(w, d) = \frac{2}{\pi} \cos^{-1}\left(\frac{w}{d}\right) - \frac{2w}{(\pi d^2)} \sqrt{d^2 - w^2} \]  

(3.5)

Using the fitted defocus diameter function and known slit width, the fractional transmission of the slit can then be plotted. The resulting function is shown in Figure 3.4. Dividing the original background-subtracted spectrum by the fractional transmission recovers the spectrum of the star without the defocus effects. This focus corrected spectrum is shown as the green line in Figure 3.6.

Beginning from this focus-corrected spectrum, the atomic absorption lines in the stellar spectrum were identified and served as a reference to identify the wavelengths corresponding to each column. These absorption features are due to the composition of the foreground gas, not the instrument response, and thus must be removed to create an accurate calibration curve. This was accomplished by bridging each inverted peak with an Akima spline to produce a smooth, de-peaked spectrum. The newly smoothed spectrum was then interpolated to a one angstrom mesh and divided by the exposure time, instrument collection area, and pixel dispersion in angstroms. Multiplying by the camera gain (3) then gives a spectrum in units of ADU s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\). This spectrum could then be compared directly to the absolutely calibrated Tüg and White spectrum in units of photons s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\). Dividing the observed spectrum by the Tüg and White spectrum gives the efficiency of the instrument in ADU/photon as a function of observation wavelength. The resulting calibration curve is shown in Figure 3.7.
Figure 3.4: Fraction of transmitted light through WISPI's slit as a function of column (corresponding to wavelength) due to the defocus effect for the observed Vega spectrum.

It should be noted that this curve has not been corrected for atmospheric effects. The source data for the calibration was an observation of Vega taken at air mass 1.40, so WISPI observations far from this air mass would require additional correction for reddening and attenuation. For WISPI observations made at or near this air mass, however, this calibration curve allows direct translation of WISPI results from ADU/s to photons/s.
Figure 3.5: The same WISPI science frame from Figure 3.3 strongly zoomed in the vertical, to show focus variations along the wavelength (horizontal) axis.
Figure 3.6: A background subtracted, wavelength-calibrated spectrum of Vega recorded by WISPI. The black curve shows the raw spectrum after background subtraction, the green curve illustrates the spectrum after correction for focus effects. Note the sharp absorption features, which were removed in the next step of the calibration process. The Hα and Hβ absorption features were used, along with several telluric lines, in mapping column numbers to wavelengths.
Figure 3.7: The WISPI calibration curve, showing ADU detected per incident photon as a function of wavelength. This curve has not been corrected for atmospheric effects, and is based on an observation taken with an air mass of 1.4.
Chapter 4 Flux Calibration of Wide Field Data

The final step in processing is to flux calibrate the wide field data set. Having accounted for atmospheric effects, it was then necessary to characterize losses within the instrument itself. Light is lost at each optical interface in the telescope, at the camera window surfaces, and in passing through the filter. The camera’s quantum efficiency at the detection wavelength is also a significant source of signal loss. In order to account for these and other systemic losses, the wide field frames must be compared to a known reference flux. Two such references were used in this work, an established absolute flux calibration of the North America Nebula (NGC 7000) and our own flux calibrated WISPI spectra. Photons incident on the CCD chip produce free electrons, which in turn produce a voltage, which is then translated on read out to analog-to-digital units (ADU) (also known as counts). The ratio of electrons in the detector well to ADU after read out is known as the camera gain. For the camera on the FSQ, the gain was 1.5. As previously noted, the gain on the WISPI camera was 3. This factor must be taken into account when considering the overall efficiency of the system. The end goal is to convert from ADU s$^{-1}$ pixel$^{-1}$ to photons s$^{-1}$ pixel$^{-1}$, allowing physical analysis of detected nebula emission.

4.1 Calibration from NGC 7000

Hα filter data can be directly compared to existing absolute Hα flux calibrations of the North America Nebula. One of the most cited sources for this calibration is from Scherb, who sampled a 49′ diameter circle on NGC 7000 and found an absolute flux of 850 ±50 rayleighs corrected to the top of the atmosphere. [139] Direct comparison to this measurement requires conversion between unit systems. The rayleigh is a CGS unit of intensity often used with airglow and auroral emission corresponding to $10^6/4\pi$ photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$. One steradian (sr) corresponds to a solid angle one radian on a side. This would be 57.3 degrees on a side, and at 3600 arcseconds per degree we get $57.3^2 \times 3600^2 = 4.255 \times 10^{10}$ arcsec$^2$.

For a distant extended source like any of our target nebulae, we can take the area of the observing optical system to be $A$ and the solid angle sampled by the optical system to be $\delta \Omega$. The solid angle subtended by a single pixel would be given by $\delta \Omega = d^2/F^2$ where $d$ is the spatial size of the detector pixel (in cm$^2$) and $F$ is the focal length of the telescope. If source radiance in photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ is $B$ then the photon count ($P$) arriving at this pixel in time $t$ is given by

$$P = B \cdot A \cdot \delta \Omega \cdot t. \quad (4.1)$$

For a telescope with diameter $D$, the area is simply $A = \pi D^2/4$. Substituting this into the previous expression along with and the previously established formulas for solid angle and conversion to rayleighs, the relation between photon count and source
radiance in rayleighs \((B_R)\) is then given by

\[
P = B_R \cdot \frac{10^6}{4\pi} \cdot \frac{\pi D^2}{4} \cdot \frac{d^2}{F^2} \cdot t \tag{4.2}
\]

for each pixel. Defining the telescope f-ratio \(f = F/D\) and simplifying, the final expression is

\[
P = 10^6 \cdot B_R \cdot \frac{1}{16f^2} \cdot d^2 \cdot t \tag{4.3}
\]

For the Apogee U9000 camera used in our observations, the pixels are 12 \(\mu m\) square. As configured for these observations, the FSQ has a 530 mm focal length and is f5. Using the 850 rayleigh measurement from Scherb and substituting these values into equation 4.3 results in a photon flux of

\[
P = 850 \times 10^6 \cdot \frac{1}{16 \times 5^2} \cdot (12 \times 10^{-4})^2 = 3.06
\]

in photons per second per pixel or, carrying the uncertainty in the original rayleigh measurement through the same relation, 3.06 \(\pm\) 0.18 photons per second per pixel. This value can be directly compared to detected ADU from the same object to ascertain a system efficiency.

A 49' sample region chosen with its center at the brightest part of NGC 7000 was selected on the atmosphere-corrected master co-add. This region is shown in Figure 4.1. The per pixel mean value in ADU given by SAOImage DS9 [148] for this region is 0.550 counts per second per pixel. The resulting calibration factor is simply 0.550/3.06 = 0.180 \(\pm\) 0.011 ADU for each incident photon. To quantify system efficiency, we simply multiply the detected ADU by the gain. The result is a system efficiency for the H\(\alpha\) filter of 0.180 \(\times\) 1.5 = 0.270 \(\pm\) 0.016 or 27\% \(\pm\) 1.6\%.

### 4.2 Calibration from WISPI

To flux calibrate all four filters, WISPI spectra of each wide field target were compared directly to the corresponding sampled region in the wide field images. At this point in the process, the wide field images had pixel values in units of ADU/s. The WISPI spectra could be determined in photons/s by comparison to the previously derived WISPI calibration curve.

A clear understanding of the region sampled by WISPI on the extended object is necessary to this process. To ascertain the dimensions of the slit projected onto the nebula, we take the slit width of 72 \(\mu m\) magnified by 180/200 due to the focal lengths of the collimator and camera, respectively. The result is an effective slit width in the image plane of 65 \(\mu m\). This slit is in the focal plane of the 400 mm focal length objective, and therefore subtends an angle of \(\tan^{-1}(0.072/400) = 0.0093\) degrees or 33.4 arcseconds in declination.

As previously noted, only a limited subset of bright, clean nebula spectra were used in the calibration, pointings and targets are listed in Table 2.5. Because of uncertainties in WISPI pointing, regions whose emission was relatively constant over
Figure 4.1: A zoomed image of the co-added, wide field master image of the North America Nebula. The green circle is the 49' diameter region enclosing the brightest part of the nebula, corresponding to the region sampled in Scherb’s absolute flux calibration of NGC 7000.

Small declination areas were particularly sought after. For purposes of this analysis, each co-added WISPI frame (e.g. Figure 4.3) was examined along side a wide field image of the corresponding object. A stretch of right ascension along the slit declination would be selected, based on bright, flat emission in the corresponding region in the wide field images. The rows of the WISPI frame corresponding to this RA range were identified, and a per column sum over these rows was extracted using ALSVID routines [76]. This data was then opened in xmgrace [151] where spectral peaks corresponding to the wide field filter bands (Hα, Hβ, [OIII], and [SII]) were identified. The background continuum around these peaks was fit with a linear regression and subtracted, and then the peak was integrated to attain a total signal. This signal was divided by the efficiency determined in the WISPI calibration process, by the collection area of the instrument (160.6 cm²), and the exposure time, then multiplied by the gain to get the collected photons/s across the entire slit. Finally, this value is divided by the solid angle sampled by WISPI’s slit projected on to the nebula (33.4” in declination multiplied by the sampled right ascension in arcseconds) to give a surface brightness in photons s⁻¹ cm⁻² arcsec⁻².

A rectangular region selection could then be created in SAOimage DS9 corresponding to the angle subtended by the slit in declination (roughly seven pixels verti-
Figure 4.2: A zoomed H/\(\alpha\) Rosette image showing the sampled region along the +5:01 line of declination. The green box is of height 33.4" corresponding to the slit width projected on the nebula. The width is 547.2" corresponding to the sampled rows in the WISPI spectral image.

An example of a sample region is illustrated in Figure 4.2. This portion of the Rosette Nebula has a declination of +5:01 and the portion selected exhibits relatively constant hydrogen emission. H\(\alpha\) surface brightness reported by SAOimage DS9 for this region in the co-added master was 0.01807 ADU arcsec\(^{-2}\) s\(^{-1}\). Dividing this by telescope collection area and multiplying by gain yields

\[
\frac{0.01807}{88.25} \cdot 1.5 = 3.07 \times 10^{-4}
\]

per arcsec\(^2\) per cm\(^2\) per second.

The corresponding WISPI frame is shown in Figure 4.3, with the region of interest corresponding to the rows between the green lines. These rows were summed and plotted in xmgrace. The H\(\alpha\) peak was identified, the background fit with a linear
regression and subtracted, and the resulting peak integrated. The spectrum, peak, and background are plotted in Figure 4.4. The integrated sum over the peak yielded 374625 counts. Dividing by telescope area, WISPI efficiency at Hα (0.163), and cumulative exposure time (2000 s) and multiplying by the gain yields

\[
\frac{374625}{160.6061 \cdot 0.163 \cdot 2000} \cdot 3 = 21.47
\]

photons per cm\(^2\) per second across the entire peak. The solid angle subtended at the nebula by this region of the slit is 33.4 arcsec \(\times\) 547.2 arcsec = \(1.83 \times 10^4\) arcsec\(^2\). Dividing 21.47 by this we find a value of \(1.17 \times 10^{-3}\) Hα photons arcsec\(^{-2}\) cm\(^{-2}\) s\(^{-1}\) from WISPI. FSQ efficiency in Hα is then given by \(3.07 \times 10^{-4} / 1.17 \times 10^{-3} = 0.261\) or 26.1%. This is comfortably within the uncertainty of the Hα efficiency determined from comparison to Scherb.

This process was performed across all four wide field filters and for all three targets, utilizing each of the spectra listed in Table 2.5. Two sample regions and their corresponding spectra were analyzed for each of the three nebula (M42, NGC 7000,
Figure 4.4: A plot of the summed rows from Figure 4.3. The total summed spectrum is shown in black, the Hα peak (flanked by [NII] lines) is highlighted in red, and the linear fit of the local background is shown in green.

and Rosette) and the calculated efficiencies were averaged and standard deviations calculated. The primary sources of error in this process are uncertainties in the WISPI pointing and some peak blending. In the Hα spectra in particular, separation of the central peak from the NII wings involved selecting a central peak width by eye, then rigorously applying that standard.

The average efficiencies are listed in Table 4.1 along with their corresponding sigmas.

Existing wide field masters were then multiplied by gain divided by efficiency (1.5 over the average efficiency from Table 4.1) to generated final flux calibrated masters. As previously noted, the Hα efficiency obtained by this method is consistent with the independent comparison to Scherb’s NGC 7000 measurement.

All four flux calibrated frames for NGC 7000 and M42 are shown in Figures 4.5 and 4.6 respectively. False color images constructed from this data are shown in Figure 4.7 for NGC 7000 and Figure 4.8 for M42. Comparable frames for the Rosette Nebula are included in the next chapter in Figure 5.9.
Figure 4.5: Final flux calibrated masters for the North America Nebula are shown for all four filters, presented on a square root scale. The $H\alpha$ data is shown from 0 to 8 photons per pixel per second. The $H\beta$ and [OIII] data are shown from 0 to 2 photons per second per pixel. The [SII] data is presented from 0 to 3 photons per pixel per second.
Figure 4.6: Final flux calibrated masters for the Orion Nebula are shown for all four filters, presented on a log scale. The Hα data is shown from 0 to 500 photons per pixel per second. The Hβ, [OIII], and [SII] data are presented from 0 to 200 photons per second per pixel.
Figure 4.7: A mosaic of the flux calibrated North America Nebula data using the Hubble palette. Red is [SII], green is H\(\alpha\), and blue is [OIII].
Figure 4.8: A mosaic of the flux calibrated Orion Nebula data using the Hubble palette. Red is [SII], green is Hα, and blue is [OIII].
Table 4.1: Summary of calculated efficiencies for the wide field system determined by comparison to WISPI spectra.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Average Efficiency</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>0.262</td>
<td>0.010</td>
</tr>
<tr>
<td>Hβ</td>
<td>0.502</td>
<td>0.067</td>
</tr>
<tr>
<td>[OIII]</td>
<td>0.376</td>
<td>0.034</td>
</tr>
<tr>
<td>[SII]</td>
<td>0.265</td>
<td>0.050</td>
</tr>
</tbody>
</table>

4.3 WISPI Air Mass Considerations

One potential source of error not addressed in the original flux calibration from WISPI spectra is the impact of varying air mass on collected WISPI spectral images. To address this concern, the previous air mass routine for Python was rewritten to allow it to work with WISPI spectra with manually entered equatorial coordinates for the target. As previously noted, the air mass of the Vega measurement from which the WISPI efficiency curve was determined was 1.4. The NGC 7000 spectra used in the calibration of the wide field imagery were also taken at 1.4 air masses, so no correction is needed here. The Rosette spectra were observed at 1.2 air masses, and the M42 spectra at 1.65 air masses, resulting in a small underestimate of reddening for the Orion spectra and a small overestimate for the Rosette spectra. To determine the impact of this, the magnitude per air mass slopes determined from Rosette photometry in the previous effective exposure time estimates were applied to directly adjust the WISPI signal counts in each filter line, adjusting the observation to the integrated peak value WISPI would have observed at air mass 1.4. As before, the relation is based on the definition of magnitude. In this case, where $B_{1.4}$ is the effective signal at air mass 1.4, $B_x$ is the signal at the observation air mass, $m$ is the previously determined slope in magnitude per air mass, and $x$ is the air mass of observation

$$B_x = B_{1.4}10^{-0.4m(x-1.4)}$$

or, solving for the effective signal at air mass 1.4

$$B_{1.4} = B_x10^{0.4m(x-1.4)}.$$  \hspace{1cm} (4.8)

The efficiency can then be recalculated, using the previously determined wide field surface brightness divided by the WISPI surface brightness corrected for air mass. The results are summarized in Table 4.2. The impact of the air mass on the resulting efficiencies is negligible, changing the original values by fractions of a percentage and falling well within the existing uncertainties. As such, the original calibrations were allowed to stand.
Table 4.2: Summary of calculated efficiencies for the wide field system determined by comparison to WISPI spectra corrected for air mass, including % change due to air mass inclusion.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Average Efficiency</th>
<th>Standard Deviation</th>
<th>Efficiency % Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>0.261</td>
<td>0.013</td>
<td>0.4%</td>
</tr>
<tr>
<td>Hβ</td>
<td>0.499</td>
<td>0.065</td>
<td>0.6%</td>
</tr>
<tr>
<td>[OIII]</td>
<td>0.376</td>
<td>0.042</td>
<td>0%</td>
</tr>
<tr>
<td>[SII]</td>
<td>0.264</td>
<td>0.044</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

4.4 Uncertainty in the Narrow Band Images

To quantize the flux uncertainty in the final flux calibrated, narrow-band, wide-field data we considered a number of sources.

**Astrometric Uncertainty**

Astrometric uncertainties in the final wide-field, narrow-band data cube slices were determined by comparison to the catalog sourced equatorial coordinates of nine bright stars across the region. Circular regions were selected in SAOImage DS9 and carefully centered on the selected stars. The center of each region, as specified in DS9, was recorded and compared to the equatorial coordinates of the target stars as listed in the SIMBAD database. Regions were imported to all four filter maps to ensure good agreement within the wide-field data itself. Ultimately, the wide field frames were found to agree with one another and with the SIMBAD catalog at a sub-arcsecond level. Stellar targets, SIMBAD catalog coordinates, and representative FSQ frame coordinates from the SII slice are detailed in Table 4.3. Note that differences in right ascension must be multiplied by a factor of 15 to translate from hour angle to degree angle.

**Photon Shot Noise**

Noise in a charge coupled detector is commonly computed as a Gaussian normal distribution \( N(x) \), with mean \( \mu \), standard deviation \( \sigma \), and variance \( \sigma^2 \).

\[
N(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(x - \mu)^2}{2\sigma^2} \right) \tag{4.9}
\]

The standard deviation in such a distribution corresponds to a 68% confidence interval, while \( 2\sigma \) corresponds to a 95% confidence interval \([10]\). The standard dev-
Table 4.3: Coordinates of target stars in the Rosette FSQ frames compared to SIMBAD database coordinates for these targets.

<table>
<thead>
<tr>
<th>Target Identifier</th>
<th>SIMBAD Coordinates RA, Dec</th>
<th>SII Frame Coordinates RA, Dec</th>
<th>Differences RA, Dec (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon 12</td>
<td>06:32:19.204 +04:51:21.59</td>
<td>06:32:19.172 +04:51:21.75</td>
<td>0.486, 0.159</td>
</tr>
<tr>
<td>HD 46223</td>
<td>06:32:09.307 +04:49:24.70</td>
<td>06:32:09.319 +04:49:24.27</td>
<td>0.182, 0.426</td>
</tr>
<tr>
<td>HD 46612</td>
<td>06:34:35.624 +04:58:04.54</td>
<td>06:34:35.598 +04:58:03.82</td>
<td>0.394, 0.719</td>
</tr>
<tr>
<td>HD 46424</td>
<td>06:33:36.109 +05:39:40.19</td>
<td>06:33:36.134 +05:39:39.23</td>
<td>0.375, 0.963</td>
</tr>
<tr>
<td>HD 45910</td>
<td>06:30:32.938 +05:52:01.20</td>
<td>06:30:32.999 +05:52:00.61</td>
<td>0.916, 0.595</td>
</tr>
<tr>
<td>HD 45545</td>
<td>06:28:16.375 +04:16:45.27</td>
<td>06:28:16.392 +04:16:45.44</td>
<td>0.255, 0.017</td>
</tr>
<tr>
<td>HD 259922</td>
<td>06:34:22.384 +04:08:47.10</td>
<td>06:34:22.368 +04:08:47.87</td>
<td>0.240, 0.773</td>
</tr>
<tr>
<td>TYC 141-6-1</td>
<td>06:28:44.239 +04:57:11.71</td>
<td>06:28:44.285 +04:57:11.81</td>
<td>0.692, 0.103</td>
</tr>
<tr>
<td>HD 46006</td>
<td>06:31:02.064 +04:30:29.32</td>
<td>06:31:02.107 +04:30:28.94</td>
<td>0.653, 0.620</td>
</tr>
</tbody>
</table>

The standard deviation ($\sigma$) in a given pixel due to random noise in the photoelectric current in the device is:

$$\sigma = \sqrt{N}$$

(4.10)

where $N$ is the photon count collected by that pixel \[52\]. To express the standard deviation as a percentage of the total signal, we find

$$\frac{\sigma}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}.$$  (4.11)

We must consider this effect individually for the FSQ filter images, the WISPI nebula images, and the WISPI Vega images upon which the WISPI spectral calibration was based.

First, we consider the standard statistical uncertainty due to photon shot noise in the Apogee Alta U9000 CCD camera used in capturing the narrow-band, wide-field data. Per the equations above, we need only that the photon shot noise is directly dependent on the photon count. For the U9000 camera, the raw count in ADU must be multiplied by a gain factor of 1.5 to restore the detected photon count. The combined exposure time for the Rosette H{$\alpha$} data is 28,800 seconds, resulting in total counts on the order of a few thousand even for the comparatively faint Rosette nebula. Consequently we find a relatively low uncertainty contribution from this effect, roughly 2% depending on the filter. To attain specific estimates, mean raw counts above background were found using SAOImage DS9 \[148\]. A circular region 0.75 degrees in radius and centered on NGC 2244 at 06:31:55 right ascension, +04:56:30 declination was selected as representative of the visible nebula, and the mean raw detector count above background were determined within that region.
Table 4.4: Mean raw counts above background for each narrow band master summed in a 1.5 degree diameter circular region. Resulting statistical uncertainty due to shot noise calculated from $1/\sqrt{N}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Raw Count (ADU)</th>
<th>Photon Count</th>
<th>Photon $\sigma$</th>
<th>% $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$\alpha$</td>
<td>5454</td>
<td>8181</td>
<td>90.45</td>
<td>1.11%</td>
</tr>
<tr>
<td>H$\beta$</td>
<td>2428</td>
<td>3642</td>
<td>60.35</td>
<td>1.66%</td>
</tr>
<tr>
<td>[OIII]</td>
<td>2350</td>
<td>3525</td>
<td>59.37</td>
<td>1.68%</td>
</tr>
<tr>
<td>[SII]</td>
<td>1516</td>
<td>2274</td>
<td>47.69</td>
<td>2.10%</td>
</tr>
<tr>
<td>WISPI Rosette</td>
<td>10000</td>
<td>30000</td>
<td>70.71</td>
<td>0.58%</td>
</tr>
<tr>
<td>WISPI Vega</td>
<td>30000</td>
<td>90000</td>
<td>300</td>
<td>0.33%</td>
</tr>
</tbody>
</table>

This raw count was then multiplied by the 1.5 gain factor to restore the photon count, and standard deviations for the standard Poisson distribution were calculated. The results are summarized in Table 4.4.

The final flux calibration of the wide-field narrow-band data is dependent on the calibration of the WISPI data, which was used as a reference. The Vega data used for that calibration had very high signal-to-noise, with even the faintest parts of the spectrum exceeding $1 \times 10^4$ counts above background. The Apogee U6 camera coupled to WISPI has a gain of 3, so the corresponding minimum photon count is $3 \times 10^4$. As a consequence, the uncertainty contribution from photon shot noise in this step is no more than $1/\sqrt{3} \times 10^4 = 0.58\%$.

Similarly, a statistical contribution from shot noise also arises in the WISPI nebula data used in the final calibration. Care was taken when regions were chosen to ensure that large sections of nebula (and consequently large spatial regions on the WISPI frames) were integrated across so as to maximize signal and minimize statistical uncertainty. A typical region was 8′ long with width defined by the slit width on the sky (33.4′). The minimum documented raw counts above background in WISPI data used in this process were $3 \times 10^4$. Applying the gain of 3 from this camera, the resulting photon noise contribution to uncertainty is $1/\sqrt{9} \times 10^4 = 0.33\%$.

Note that the uncertainty due to photon shot noise in the WISPI data would apply equally to all pixels in a wide-field frame. Details of all uncertainties due to photon shot noise are summarized in Table 4.4.

**Statistical Uncertainty Factors**

In addition to uncertainty due to random shot noise, the final calibration of the wide-field data is also impacted by additional statistical uncertainties. The calibration factors discussed in this subsection apply equally to every pixel in the frame, and consequently represent an uncertainty in the calibration zero-point only.

The documented atmospheric correction process induces additional calibration uncertainty. The original magnitude-per-airmass slope fits carried a small standard deviation for each filter analyzed, as documented in Table 3.1. These standard devi-
Table 4.5: Factors determining the contribution of the airmass reddening correction to flux uncertainty.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Mean Airmass</th>
<th>Slope $\sigma$</th>
<th>Magnitude $\sigma$</th>
<th>% $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$\alpha$</td>
<td>1.495</td>
<td>0.00876</td>
<td>0.01309</td>
<td>1.20%</td>
</tr>
<tr>
<td>H$\beta$</td>
<td>1.422</td>
<td>0.01926</td>
<td>0.02738</td>
<td>2.49%</td>
</tr>
<tr>
<td>[OIII]</td>
<td>1.417</td>
<td>0.03412</td>
<td>0.04834</td>
<td>4.36%</td>
</tr>
<tr>
<td>[SII]</td>
<td>1.570</td>
<td>0.01323</td>
<td>0.02077</td>
<td>1.90%</td>
</tr>
</tbody>
</table>

Ratios are in magnitude, so must be translated back to an absolute ratio to produce a percentage uncertainty for inclusion in this analysis. These values are also per airmass, so a Python script was constructed to find the mean airmass of observation for each filter. The magnitude standard deviation for mean airmass can be determined by simply multiplying the sigma for each filter by the mean observation for that filter. To convert this magnitude sigma ($\sigma_m$) to a percentage flux uncertainty ($\sigma$), we again use the magnitude relation

$$\sigma = 1 - 10^{-\frac{2}{5}\sigma_m}.$$  \hspace{1cm} (4.12)

Table 4.5 shows the mean airmass, slope uncertainty, resulting magnitude uncertainty ($\sigma_m$), and resulting percentage flux uncertainty ($\sigma$).

The largest uncertainty source arises from the calibration process itself. As documented earlier in Table 4.3, inconsistencies in the calculated efficiencies for each filter were characterized by a standard deviation. It should be noted that this deviation may in part be a consequence of other factors previously considered, but in the interests of producing a conservative estimate of the over-all flux uncertainty in the calibration we include these standard deviations as additional independent uncertainty sources. To produce percent uncertainties, we simply take the standard deviation in the efficiency for each filter and divide by the determined efficiency for that filter, producing $\sigma$’s of 3.8% for H$\alpha$, 13.3% for H$\beta$, 9.0% for [OIII], 18.8% for [SII].

**Combined Uncertainty**

Combining these factors into a final flux uncertainty encompassing all discussed factors is complicated by the difficulty of accounting for dependence, especially in the final calibration factor, on the previously accounted for uncertainty sources. Ultimately, a conservative estimate can be arrived at by treating each uncertainty as arising independently and then adding them in quadrature [10]. Table 4.6 presents quadrature combined $\sigma$ values for the final uncertainty estimate including both photon noise and zero point effects which may serve as a final estimate of the calibration accuracy in any single pixel within the wide-field data.
Table 4.6: 68% confidence uncertainty estimates for the absolute flux calibration of the wide-field, narrow-band data.

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$\alpha$</td>
<td>4.19%</td>
</tr>
<tr>
<td>H$\beta$</td>
<td>13.65%</td>
</tr>
<tr>
<td>[OIII]</td>
<td>10.16%</td>
</tr>
<tr>
<td>[SII]</td>
<td>19.02%</td>
</tr>
</tbody>
</table>

It is important to note that these are very conservative estimates. In addition to the interdependency question, we looked at photon noise in terms of single pixels, while most results derived from this data involved summing over significant areas, thus reducing the impact of these noise effects. Finally, recall that the bulk of this uncertainty arises from factors affecting all pixels in a map in the same way, essentially an uncertainty in the zero point of the calibration. Individual pixel uncertainties relative to one another are purely a product of the detector uncertainty at time of collection, detailed in the first four lines of Table 4.4. These small uncertainties are further mitigated by summing over more than one pixel.
The narrow band, wide field data collected from Moore Observatory allowed insight into a specific subset of physical processes within the Rosette nebula, providing a foundation for understanding the foreground extinction as well as the ionization state and aspects of the composition of the gas in the nebula. However, a more comprehensive analysis required a more complete view of the object. In order to better understand the structure and processes within the Rosette Nebula, the calibrated wide field frames were combined with observations from radio, microwave, infrared, and ultraviolet archival sources to create a multispectral data cube. Each band provides additional, complementary information and constrains models of the physics within the nebula.

Important sources of radio emission in HII regions include the 21 cm (1428 MHz) line of neutral hydrogen (HI), along with extensive emission from free-free electron scatter, which characterizes the electron temperature and density in the gas [25].

Microwave emission in HII regions arises from a rich variety of sources, including synchrotron emission, free-free emission, thermal dust emission, CO lines, and anomalous microwave emission which may be due to spinning microscopic dust [120]. Disentangling these various sources can be a challenge, and having access to a variety of frequencies is vital to interpreting emission in a complex region like the Rosette. Cosmic microwave background is also present across the region of interest, of course, but contributes at most 2% to the total signal [124].

Infrared emission in HII regions is primarily thermal emission from dust. Infrared observations provide unique insight into the size and distribution of dust grains warmed by the interstellar radiation field. Of particular interest is emission from polycyclic aromatic hydrocarbons, little-understood complex organic molecules with broadened line emission known at 3.3, 6.2, 7.7, 8.6, and 11.3 μm [168]. Because dust is such a dominant presence throughout the Rosette region and plays a key role in understanding the geometry and dynamics of the nebula, a wide variety of infrared sources were integrated into the data cube. Several prominent forbidden lines also exist in the far infrared, including the 158 μm line of [CII], the 88 μm line of [OII], and the 63.2 μm line of [OI]. These lines can provide useful diagnostics regarding the temperature and density of portions of the nebula which are heavily attenuated and thus hard to observe in visible light [166]. The 4.6 μ CO line is also a useful tracer of the interior structure of the dust envelopes around young stellar objects [136].

Ultraviolet emission in the included ultraviolet band, in addition to the bright OB stellar sources, arises from a diversity of atomic line sources including neutral and singly ionized helium (including a portion of the Paschen series) and forbidden transitions in [OIII], [CII], [CIII], [SiII], [SiIII], NeIII and others [78]. In addition, studies of M42 suggest a significant contribution of UV emission may stem from stellar radiation scattering off of dust [46].

The cube consists of spatially aligned slices, resampled to the same spatial scale, where each slice corresponds to a different wavelength or spectral band. With the
exception of ground based radio observations from the Effelsberg 100m dish and our own wide field narrow band observations, all selected data were from space based instruments. A summary of data cube slices is given in Table 5.1. Each included band was assigned an index number, in order of increasing frequency, for easy reference. Band coverage is illustrated in Figure 5.1.

The cube needed to be aligned in right ascension and declination, with all frames on the same spatial scale, so that direct comparisons could be made from slice to slice across the various available wavelength bands. To this end, a spatial scale of 1 arcsecond per pixel was selected to provide ease of calculation and comparison across all frames. This pixel scale oversamples the high resolution data sources, such as our own FSQ observations, while making comparison to narrow field data more straightforward. In order to encompass the entire ionized region, a field 2 degrees on a side was chosen, corresponding to a frame size of 7200 by 7200 pixels. The field was aligned according to standard J2000 equatorial coordinates and centered at 6\(^{h}\) 31\(^{\prime}\) 55\(^{\prime\prime}\) right ascension +4\(^{\circ}\) 56\(^{\prime}\) 34\(^{\prime\prime}\) declination, which corresponds to the center of NGC 2244. Each slice in the stack was resampled to this size and scale, but in order for meaningful physical comparisons to be made it was also necessary to bring all flux calibrated pixel values to the same units.

It was decided to put all frames in the cube on an energy flux per pixel scale, specifically in units of Watts per square meter of collection area per 1 arcsecond square pixel (W m\(^{-2}\) pix\(^{-1}\) or equivalently W m\(^{-2}\) arcsec\(^{-2}\)) at the top of the atmosphere. This allows signal integration of regions of interest within the extended emission, and provides easy direct comparison from passband to passband. It must be noted, however, that both the frequency and angular pixel measure for each observation was retained in the header for each frame, so that per steradian and per Hertz values could be recovered as needed.

### 5.1 Effelsberg 100 m Observations

Because the Rosette has such a large angular size on the sky, wide field single dish radio data covering the entire region were limited. Among the most recent of the available data were 1410 and 4750 MHz continuum maps by Celnik [25], and a 2700 MHz continuum map by Graham [55]. Due to their age, these data were presented in the form of printed contour maps. Fortunately, calibration information is included in tabular form, allowing a flux calibrated map to be recreated. The original digital data are not available.

The Celnik 1410 MHz and 4750 MHz observations were made on the Effelsberg 100 m instrument. For the 1410 MHz map, the sampled region was centered on the central cluster, with a 2.6 x 2.6 degree field. Brightness temperature in Kelvin was measured over four discrete observations, and the resulting values were averaged to create the published contour map. The 4750 MHz observations were the result of a scan of continuum intensity across right ascension and declination in a 3 x 3 degree grid. Again, a contour map in brightness temperature (Kelvin) resulted, determined from total power measurements of calibration point sources [25].
Table 5.1: A complete list of all bands included in the data cube, along with identifying index numbers and a summary of physical processes responsible for this type of emission.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Band Index</th>
<th>Wavelengths (m)</th>
<th>Frequencies (Hz)</th>
<th>Nebula Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effelsberg 100 m</td>
<td>1</td>
<td>(2.127 \times 10^{-1})</td>
<td>(1.410 \times 10^9)</td>
<td>HI 21 cm line and free-free emission.</td>
</tr>
<tr>
<td>WMAP</td>
<td>1</td>
<td>(1.000 \times 10^{-2})</td>
<td>(3.000 \times 10^{10})</td>
<td>Free-free, thermal dust, synchrotron, thermal dust, CO line, &amp; anomalous microwave emission</td>
</tr>
<tr>
<td>Planck</td>
<td>1</td>
<td>(8.500 \times 10^{-3})</td>
<td>(6.080 \times 10^{10})</td>
<td>(likely due to spinning dust).</td>
</tr>
<tr>
<td>Akari</td>
<td>18</td>
<td>(1.600 \times 10^{-4})</td>
<td>(1.875 \times 10^{12})</td>
<td>Thermal continuum from dust, line emission from [OII], [CII] and others.</td>
</tr>
<tr>
<td>IRAS</td>
<td>20</td>
<td>(1.000 \times 10^{-4})</td>
<td>(3.000 \times 10^{12})</td>
<td>Thermal dust emission, PAH band emission.</td>
</tr>
<tr>
<td>MSX</td>
<td>26</td>
<td>(2.134 \times 10^{-5})</td>
<td>(1.410 \times 10^{13})</td>
<td>Thermal dust emission, PAH band emission</td>
</tr>
<tr>
<td>WISE</td>
<td>25</td>
<td>(2.200 \times 10^{-5})</td>
<td>(1.364 \times 10^{13})</td>
<td>Thermal dust emission, PAH band emission, and CO line emission</td>
</tr>
<tr>
<td>FSQ</td>
<td>34</td>
<td>(6.723 \times 10^{-7})</td>
<td>(4.462 \times 10^{14})</td>
<td>Hydrogen, oxygen, and sulfur atomic line emission</td>
</tr>
<tr>
<td>GALEX</td>
<td>38</td>
<td>(2.271 \times 10^{-7})</td>
<td>(1.321 \times 10^{15})</td>
<td>Helium line emission UV dust scatter</td>
</tr>
</tbody>
</table>
The Graham 2700 MHz data were gathered from the Gregorian focus of the Effelsberg 100m instrument, resulting in a 4.4 arcminute beam that was smoothed to a 10 arcminute resolution in processing. Raster scans across a 5 by 7 degree grid centered on the supernova remnant captured the entire Rosette field. Again, absolute brightness temperature was determined from comparison to known point sources [55].

In order to make this information compatible with the multispectral data set, it was necessary to digitize the contours and process those into an interpolated radio-frequency map. This was accomplished through the use of Frederic V. Hessman’s “Figure Calibration” plug-in for ImageJ, in combination with Karen Collins’ AstroImageJ processor [35]. Data points were identified by eye and captured point-by-point from the original published Figures. Each contour was followed carefully by hand, and points were captured with sufficient density to recreate the original contour curves. Individual contours were stored separately as a list of coordinates, and a python script was written to assign the known contour values on each captured contour line to their corresponding spatial coordinates. A master database was then constructed including all contours for a given map.
Table 5.2: Summary of beam characteristics and conversion factors for Graham and Celnik observations on the Effelsberg 100 m dish [25] [55] [129].

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$\Delta \nu$ (MHz)</th>
<th>HPBW (arcmin)</th>
<th>$T_b/S$ (K/Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1410</td>
<td>10</td>
<td>9.24</td>
<td>2.00</td>
</tr>
<tr>
<td>2700</td>
<td>80</td>
<td>4.4</td>
<td>2.58</td>
</tr>
<tr>
<td>4750</td>
<td>500</td>
<td>2.43</td>
<td>2.55</td>
</tr>
</tbody>
</table>

Because the Celnik data were in B1950 equatorial coordinates, and the Graham data were in galactic coordinates, it was also necessary to import conversion routines to the Python code in order to translate the spatial coordinates to J2000 equatorial coordinates. Finally, a Python routine was constructed which interpolated the sparse contours into an oversampled map of the Rosette at each radio frequency. Several interpolation options were tried, but it was decided that a linear interpolation resulted in the most accurate recreation of the published data and avoided the fitting artifacts which appeared in cubic spline and other more complex fits.

Utilizing PyFits, a routine was built to export the interpolated data into the .fits format. Appropriate world coordinate system (WCS) headers were constructed by reference to the coordinate overlay on the original published contour maps so that the resulting slices could be compared to other project data and directly incorporated into the data cube.

The resolution of the contour files was initially set roughly equal to the resolution of the FSQ wide field frames, with a 4.673 arcsecond pixel. In resampling to the data cube standard 1 arcsecond per pixel resolution, SWarp automatically reduced the per pixel signal value by a factor of $4.637^2 = 21.81$. Since the recorded contour values are in brightness temperature, however, there is no spatial dependence, and for purposes of later converting to energy units it was necessary to multiply this factor back in to the data.

The translated contour maps give brightness temperature in Kelvin as a function of position, with the spatial scaling of that data dependent on the half power beam width (HPBW) used in collection. That spatial scaling had to be restored before the temperature values could be converted to energy. Each of the three frequencies corresponds to a different beam geometry, and a different conversion factor between brightness temperature and flux in Jansky ($T_B/S$). Essential details of each observation are summarized in Table 5.2.

One Jansky is equal to $10^{-26}$ W m$^{-2}$ Hz$^{-1}$. To determine a conversion factor from brightness temperature to W/m$^2$ for each band, we multiplied by this factor, divided by the $T_B/S$ factor in Table 5.2, and multiplied by the bandwidth ($\Delta \nu$) to remove
Table 5.3: Summary of calculated conversion factors for the Effelsberg radio data.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>W/m² per K</th>
<th>Ω (sr)</th>
<th>W m⁻² sr⁻¹ per K</th>
<th>for W m⁻² pix⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1410 MHz</td>
<td>5.000×10⁻²⁰</td>
<td>8.108×10⁻⁶</td>
<td>6.167×10⁻¹³</td>
<td>3.1603×10⁻²⁴</td>
</tr>
<tr>
<td>2700 MHz</td>
<td>31.01×10⁻²⁰</td>
<td>1.856×10⁻⁶</td>
<td>1.671×10⁻¹³</td>
<td>8.5648×10⁻²³</td>
</tr>
<tr>
<td>4750 MHz</td>
<td>196.10×10⁻²⁰</td>
<td>5.662×10⁻⁷</td>
<td>3.462×10⁻¹²</td>
<td>1.7745×10⁻²¹</td>
</tr>
</tbody>
</table>

the frequency dependence. As an example, for the 1410 MHz band,

\[
0.5 \text{ Jy/K} \cdot 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \cdot 10 \times 10^6 \text{ Hz} = 5.000 \times 10^{-20} \text{ W/m}^2 \text{ per K}. \quad (5.1)
\]

A spatial dependence needed to be added with the ultimate goal of bring this to W m⁻² arcsec⁻². Knowing the HPBW we can convert to a solid angle dependence in steradians (Ω) using the relation

\[
\Omega = \frac{\pi \theta^2}{4 \ln(2)} \quad (5.2)
\]

where \( \theta \) is the HPBW in radians. Dividing the previous conversion factor by Ω resulted in a combined factor which converts to W m⁻² sr⁻¹ from brightness temperature in Kelvin. The final steps were to convert from steradians to arcsec² via the factor

\[
1 \text{ arcsec}^2 = 2.35044 \times 10^{-11} \text{ sr} \quad (5.3)
\]

and multiply by the spatial scaling factor of 21.81 to restore the proper flux scaling. Table 5.3 summarizes these factors and gives the final conversion factor.

This final factor was multiplied through each slice after SWarp rescaling to produce final, data cube standard maps in each frequency. These final maps are shown in Figure 5.2.

Absolute calibration uncertainties of 1% or less are specified for each radio data set, but a larger concern is the spatial uncertainty arising from interpolation of the printed contour maps. Using a linear interpolation, a reasonable per-pixel flux uncertainty would be one half contour step, which could then be translated to an absolute flux energy uncertainty in the final data cube slices via the conversion factors previously determined. A summary of the resulting per pixel uncertainties if given in Table 5.4. It should be noted, however, that photometric applications of this data virtually always involve integration over a larger area, significantly reducing the spatial uncertainty below the single-pixel value specified here.

### 5.2 Wilkinson Microwave Anisotropy Probe (WMAP) Observations

Two recent all-sky microwave surveys, the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck mission, were focused on mapping the cosmic microwave...
Figure 5.2: Final flux calibrated energy maps of the Rosette region at 1410 MHz, 2700 MHz, and 4750 MHz displayed on individual square root flux scales. Original data from [25] and [55].
Table 5.4: Single pixel flux and spatial uncertainties in the Rosette interpolated radio data. Flux uncertainties and contour step sizes from [25] [55] [129].

<table>
<thead>
<tr>
<th>Band</th>
<th>Flux Uncertainty</th>
<th>Spatial Uncertainty (K)</th>
<th>Spatial Uncertainty (W m$^{-2}$ pix$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1410 MHz</td>
<td>1%</td>
<td>0.4</td>
<td>$5.80 \times 10^{-26}$</td>
</tr>
<tr>
<td>2700 MHz</td>
<td>1%</td>
<td>0.165</td>
<td>$6.46 \times 10^{-25}$</td>
</tr>
<tr>
<td>4750 MHz</td>
<td>0.4%</td>
<td>0.1</td>
<td>$8.16 \times 10^{-24}$</td>
</tr>
</tbody>
</table>

Table 5.5: Factors involved in the conversion from default WMAP brightness in millikelvin to energy units of W/m$^2$. Filter frequencies and Γ’s from [110].

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\nu$ (GHz)</th>
<th>$\Delta \nu$ (GHz)</th>
<th>$\Gamma$ (mK/Jy)</th>
<th>W/m$^2$ per mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>22.8</td>
<td>5.5</td>
<td>0.269</td>
<td>$20.45 \times 10^{-17}$</td>
</tr>
<tr>
<td>Ka</td>
<td>33.0</td>
<td>7.0</td>
<td>0.213</td>
<td>$32.86 \times 10^{-17}$</td>
</tr>
<tr>
<td>Q</td>
<td>40.7</td>
<td>8.3</td>
<td>0.222</td>
<td>$37.38 \times 10^{-17}$</td>
</tr>
<tr>
<td>V</td>
<td>60.8</td>
<td>14.0</td>
<td>0.212</td>
<td>$66.04 \times 10^{-17}$</td>
</tr>
<tr>
<td>W</td>
<td>93.5</td>
<td>20.5</td>
<td>0.182</td>
<td>$112.63 \times 10^{-17}$</td>
</tr>
</tbody>
</table>

background, but in the course of these surveys low resolution maps of the entire Rosette region were produced at many microwave frequencies. The WMAP instrument was composed of a set of back-to-back 1.4 m and 1.6 m reflectors in a Gregorian configuration coupled to high electron mobility transistor amplifiers. The instrument mapped the CMB in five bands, centered at 22.8 GHz (K), 33.0 GHz (Ka), 40.7 GHz (Q), 60.8 GHz (V), and 93.5 GHz (W). [6]. Half power beam widths were on the order of tenths of a degree, with milliKelvin sensitivities.

WMAP data were retrieved from the Legacy Archive for Microwave Background Data Analysis (LAMBDA). These data were presented in brightness temperature units of millikelvin, so integration into the data cube required a very similar procedure to that used for the Effelsberg data. Once again, the result was highly dependent on the beam geometry, so it was necessary to utilize the solid angle ($\Omega$) subtended by the which was in this case provided in the instrument documentation for each bandpass [110]. The $\Delta \nu$ along with a conversion factor ($\Gamma$) from microK to Jansky was also provided for each band by the WMAP collaboration [110]. For each band, then, a conversion factor from the millikelvin in the base data to units of W m$^2$ per mK was generated by multiplying the known $10^{-26}$ W/m$^2$ per Jansky factor by the bandwidth ($\Delta \nu$) and dividing by $\Gamma$. Table 5.5 summarizes the known values and intermediate conversion factors, while Eq. 5.4 shows a sample calculation for the K band.
Table 5.6: Factors from beam geometry involved in converting WMAP data to W/m$^2$ per pixel in the data cube. Filter frequencies and Ω’s from [110].

<table>
<thead>
<tr>
<th>Filter</th>
<th>W/m$^2$ per mK</th>
<th>Ω (sr)</th>
<th>for W m$^{-2}$ pix$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>20.45×10$^{-17}$</td>
<td>2.39×10$^{-4}$</td>
<td>2.011×10$^{-23}$</td>
</tr>
<tr>
<td>Ka</td>
<td>32.86×10$^{-17}$</td>
<td>1.43×10$^{-4}$</td>
<td>5.401×10$^{-23}$</td>
</tr>
<tr>
<td>Q</td>
<td>37.38×10$^{-17}$</td>
<td>0.889×10$^{-4}$</td>
<td>9.883×10$^{-23}$</td>
</tr>
<tr>
<td>V</td>
<td>66.04×10$^{-17}$</td>
<td>0.417×10$^{-4}$</td>
<td>37.23×10$^{-23}$</td>
</tr>
<tr>
<td>W</td>
<td>112.63×10$^{-17}$</td>
<td>0.206×10$^{-4}$</td>
<td>128.5×10$^{-23}$</td>
</tr>
</tbody>
</table>

$\frac{10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ Jy}^{-1}}{0.269 \text{ mK Jy}^{-1}} \cdot 5.5 \times 10^9 \text{ Hz} = 20.45 \times 10^{-17} \text{ W/m}^2 \text{ per millikelvin } (5.4)$

The intermediate factors calculated in Table 5.5 were divided by Ω in steradians to introduce the needed angular dependence, and then multiplied by the 2.3504×10$^{-11}$ arcsec$^2$ per steradian to generate a final conversion factor from millikelvin to W/m$^2$ per pixel. The final resulting conversion factors are summarized in Table 5.6 and a sample calculation for the K band is shown in Eq. 5.5. Data from each band was resampled to the one arcsecond per pixel spatial scale and the conversion factor was applied to the flux by script to produce final data cube slices.

Per recent analysis by the WMAP collaboration, the uncertainty in the absolute calibration is conservatively placed at 0.2% based on end-to-end gain recovery simulations.[7]

$$\frac{20.45 \times 10^{-17} \text{ W/m}^{-2} \text{ mK}^{-1}}{2.39 \times 10^{-4} \text{ sr}} \cdot 2.3504 \times 10^{11} \text{ sr arcsec}^{-2} = 2.011 \times 10^{-23} \text{ for final units of W m}^{-2} \text{ pix}^{-1}$$ (5.5)

5.3 Planck Observations

The Planck instrument is composed of a heavily baffled oblong reflector 1.9 x 1.5 m across which reflects microwave radiation toward the coplanar feed horns for the low frequency instrument (LFI) and high frequency instrument (HFI) located in the focal plane. The LFI radiometers are comprised of indium phosphide high electron mobility transistors, while the HFI detectors are an array of 52 bolometers. LFI mapped the sky in 30 GHz, 44 GHz, and 70 GHz bands with milliJansky sensitivities but comparatively large HPBW’s (and thus low resolutions) on the order of half a degree. HFI surveyed the sky in 100 GHz, 143 GHz, 217 GHz, 353 GHz, 545 GHz, and 857 GHz bands with similar sensitivities and HPBW’s on the order of 5 arcminutes [154].
Figure 5.3: A sample of WMAP flux calibrated energy maps of the Rosette region. Pictured bands are bands K (22.8 GHz), V (60.8 GHz) and W (93.5 GHz). All data displayed on individual square root flux scales.

Table 5.7: Factors involved in converting high frequency Planck data to W m$^{-2}$ arcsec$^{-2}$ in the data cube.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$\Delta \nu$ (GHz)</th>
<th>Source Pix (arcsec)</th>
<th>for W m$^{-2}$ arcsec$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>545</td>
<td>171.3</td>
<td>60</td>
<td>$14.494 \times 10^{-17}$</td>
</tr>
<tr>
<td>857</td>
<td>245.9</td>
<td>60</td>
<td>$20.807 \times 10^{-17}$</td>
</tr>
</tbody>
</table>

Planck survey data were provided via the Infrared Science Archive (IRSA) as a collection of individual beam pointings. These were combined into a single map at each frequency using SWarp software [9], after minor modifications to make the WCS headers compatible. Two different calibrations were used by the Planck team. The resulting publicly available maps at 545 GHz and 857 GHz are provided in MJy/sr, while the lower frequency data is provided in temperature (in K$_{CMB}$) which requires a more extensive conversion.

For the two highest frequency bands, conversion to W m$^{-2}$ arcsec$^{-2}$ involved multiplying by $10^{-20}$ to convert from MJy to W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$, multiplying by the bandwidth ($\Delta \nu$) to remove the frequency dependence, and then by a factor of $2.3504 \times 10^{11}$ to convert from a steradian solid angle to an arcsec$^2$ angular scale. A geometric correction equal to the square of the original pixel size in arcsec must also again be applied to undo SWarp’s scaling of the signal in proportion to the pixel resolution. Table 5.7 summarizes these factors and gives final conversion factors between the original downloaded data and the final data cube compatible versions. Eq. 5.6 shows an example calculation for the 857 GHz band.
Table 5.8: Factors involved in converting mid and low frequency Planck data to W m$^{-2}$ arcsec$^{-2}$ in the data cube. Temperature to MJy/sr conversion factors sourced from [121].

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>MJy·sr$^{-1}$/K CMB</th>
<th>$\Delta \nu$ (GHz)</th>
<th>Source Pix (arcsec)</th>
<th>for W m$^{-2}$ arcsec$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>24.255</td>
<td>10.0</td>
<td>120</td>
<td>$8.209\times10^{-15}$</td>
</tr>
<tr>
<td>44</td>
<td>56.094</td>
<td>10.0</td>
<td>120</td>
<td>$1.898\times10^{-15}$</td>
</tr>
<tr>
<td>70</td>
<td>131.24</td>
<td>16.0</td>
<td>120</td>
<td>$7.1071\times10^{-15}$</td>
</tr>
<tr>
<td>100</td>
<td>241.40</td>
<td>32.9</td>
<td>60</td>
<td>$6.7201\times10^{-15}$</td>
</tr>
<tr>
<td>143</td>
<td>373.67</td>
<td>45.8</td>
<td>60</td>
<td>$14.481\times10^{-15}$</td>
</tr>
<tr>
<td>217</td>
<td>486.24</td>
<td>64.5</td>
<td>60</td>
<td>$26.537\times10^{-15}$</td>
</tr>
<tr>
<td>353</td>
<td>288.04</td>
<td>101.4</td>
<td>60</td>
<td>$24.714\times10^{-15}$</td>
</tr>
</tbody>
</table>

\(10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ per MJy} \cdot 245.9 \times 10^9 \text{Hz} \cdot 2.3504 \times 10^{-11} \text{ arcsec}^2/\text{sr} \cdot 60^2 = 20.807 \times 10^{-17} \text{ for final units of W m}^{-2} \text{ arcsec}^{-2}\)  
(5.6)

For the remaining Planck bands, CMB temperature in Kelvin must first be converted to flux in MJy/sr via a multiplicative factor, at which point the previous conversion process may be applied. Conversion multipliers for each filter are provided in Planck collaboration documentation of 2015 results [121]. Table 5.8 summarizes all factors involved in converting these bands to final data cube compatible units. Eq. 5.7 shows an example calculation for the 30 GHz band, which is distinct from the earlier example only in the application of a temperature to MJy/sr multiplier as the first step.

\(24.255 \cdot 10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ per MJy} \cdot 245.9 \times 10^9 \text{Hz} \cdot 2.3504 \times 10^{-11} \text{ arcsec}^2/\text{sr} \cdot 60^2 = 20.807 \times 10^{-17} \text{ for final units of W m}^{-2} \text{ arcsec}^{-2}\)  
(5.7)

Uncertainties in the Planck data are documented in Table 5.9.

5.4 Akari Observations

The Akari telescope performed a comprehensive survey of the sky in a variety of near and far infrared bands. Of particular interest to this project were the results collected by the Far-Infrared Surveyor (FIS) which provides the highest resolution far infrared imaging available which covers the entire Rosette region.

Akari was equipped with a Ritchey-Chretien telescope at f/6 with an effective aperture of 68.5 cm, paired with two infrared instruments in the focal plane, resulting in a 38' radius field of view. The FIS was comprised of Ge:Ga and stressed Ge:Ga
Figure 5.4: Planck flux calibrated energy maps of the Rosette region in data cube format. All data displayed on individual square root flux scales.
Table 5.9: Documented Planck flux calibration uncertainties at time of retrieval. Planck LFI uncertainties from [125], HFI uncertainties from [122]. Higher uncertainties for the 545 and 857 GHz data are a result of calibration by reference to a Jovian model with an additional intrinsic uncertainty.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Frequency (GHz)</th>
<th>Calibration Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFI</td>
<td>30</td>
<td>0.35%</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>0.26%</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>0.20%</td>
</tr>
<tr>
<td>HFI</td>
<td>100</td>
<td>0.09%</td>
</tr>
<tr>
<td></td>
<td>143</td>
<td>0.07%</td>
</tr>
<tr>
<td></td>
<td>217</td>
<td>0.16%</td>
</tr>
<tr>
<td></td>
<td>353</td>
<td>0.78%</td>
</tr>
<tr>
<td></td>
<td>545</td>
<td>6.1%</td>
</tr>
<tr>
<td></td>
<td>857</td>
<td>6.4%</td>
</tr>
</tbody>
</table>

Table 5.10: Factors involved in converting Akari data to W m\(^{-2}\) arcsec\(^{-2}\) in the data cube. Bandwidth data from [168].

<table>
<thead>
<tr>
<th>Filter</th>
<th>(\lambda) ((\mu)m)</th>
<th>(\nu) (THz)</th>
<th>(\Delta\nu) (THz)</th>
<th>for W m(^{-2}) arcsec(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N60</td>
<td>65</td>
<td>4.615</td>
<td>2.250</td>
<td>1.1897\times10(^{-16})</td>
</tr>
<tr>
<td>WIDE-S</td>
<td>90</td>
<td>3.333</td>
<td>2.270</td>
<td>1.2003\times10(^{-16})</td>
</tr>
<tr>
<td>WIDE-L</td>
<td>140</td>
<td>2.143</td>
<td>1.060</td>
<td>5.6048\times10(^{-17})</td>
</tr>
<tr>
<td>N160</td>
<td>160</td>
<td>1.875</td>
<td>0.476</td>
<td>2.5169\times10(^{-17})</td>
</tr>
</tbody>
</table>

detector arrays which capture far infrared radiation in four bands of varying bandwidth. The two narrower bands were N60, centered at 65 \(\mu\)m, and N160, centered at 160 \(\mu\)m. The wider far infrared bands were WIDE-S, centered at 90 \(\mu\)m, and WIDE-L, centered at 140 \(\mu\)m. The N60 and WIDE-S maps have resolutions of 29".5, while the WIDE-L and N160 maps have resolutions of 49".1 [103]. Data in all four bands was incorporated into the Rosette data cube.

Akari data were retrieved through the IRSA. Maps were presented in units of MJy/sr, as with Planck 857 GHz, so the same conversion process was applied. For all filters, the original source pixel size was 15 arcseconds, so a geometric correction factor of 15\(^2\) was included to restore the correct value after SWarp resampling to 1 arcsecond pixels. A summary of inputs and resulting final conversion factors are presented in Table 5.10.

SWarp was used to resample the data to the correct pixel scale and region and the resulting pixel values were multiplied by the conversion factor. Images of the final
Figure 5.5: Akari flux calibrated energy maps of the Rosette region in data cube format. Displayed bands with mean wavelengths: N60 (65 µm), WIDE-S (90 µm), WIDE-L (140 µm) and N160 (160 µm). Each frame displayed on individual square root flux scales.

Takita et al. (2015) estimates that an absolute accuracy of 20% was achieved for all the bands with intensities of 6 MJy sr$^{-1}$ for N60, 2 MJy sr$^{-1}$ for WIDE-S, and $\geq$15 MJy sr$^{-1}$ for WIDE-L and N160. These are essentially worst case estimates, with brighter regions producing considerably better absolute accuracies. Utilizing the detailed accuracy breakdown in Takita, and average Rosette fluxes in each Akari band, we have produced mean calibration uncertainties for the Rosette Akari data as outlined in Table 5.11 [153].
Table 5.11: Flux calibration uncertainties in the Rosette Akari data determined by comparison of mean Rosette flux in each band to uncertainty specifications in Takita et al. [153].

<table>
<thead>
<tr>
<th>Filter</th>
<th>Wavelength $\lambda$ ($\mu$m)</th>
<th>Mean Rosette Flux (MJy/sr)</th>
<th>Flux Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>N60</td>
<td>65</td>
<td>90</td>
<td>12.5%</td>
</tr>
<tr>
<td>WIDE-S</td>
<td>90</td>
<td>120</td>
<td>5.7%</td>
</tr>
<tr>
<td>WIDE-L</td>
<td>140</td>
<td>284</td>
<td>9.8%</td>
</tr>
<tr>
<td>N160</td>
<td>160</td>
<td>270</td>
<td>10.3%</td>
</tr>
</tbody>
</table>

5.5 Infrared Astronomical Satellite (IRAS) Observations

In late 1983 the Infrared Astronomical Satellite (IRAS) completed a survey of the sky in 12, 24, 60, and 100 $\mu$m wavelength bands referenced as IRAS 1, 2, 3, and 4 respectively. The result is one of most extensively utilized collections of sky brightness maps in infrared astronomy. While the 4 - 6' resolution of these observations is low compared to more modern offerings, they are still ideal for studying large scale geometry in regions like the Rosette [5].

The IRAS satellite housed an 0.57 m aperture f/9.6 Ritchey-Chretien telescope utilizing cryogenically cooled beryllium mirrors and a collection of baffles which guided light to a collection of 62 focal plane infrared detectors coupled to field lenses and spectral filters. Si:As detectors with an average sensitivities of 0.7 Jy were used for 12 $\mu$m observations, Si:Sb detectors with average sensitivities of 0.65 Jy were used at 25 $\mu$m. The long wavelength observations were captured by Ge:Ga detectors, with sensitivities averaging 0.85 Jy 60 $\mu$m and 3.0 Jy at 100 $\mu$m [105]. While the IRAS sky survey was not originally well-calibrated for absolute radiometry, the subsequent IRIS reprocessing by Miville [100] drastically reduced photometric uncertainty. These new flux calibrated data sets contained only a 5% uncertainty across all bands at spatial scales of 1.25 degrees or less, though an additional uncertainty was introduced due to unknown aspects of the spectral response. This additional uncertainty was 6, 10, 3, and 10% for the 100, 60, 25, and 12 $\mu$m bands respectively. Combining these two uncertainties in quadrature, we find cumulative flux uncertainties as summarized in Table 5.12 [100].

IRIS reprocessed data from IRAS was retrieved from the IRSA. Base units were again MJy/sr, so the reduction process utilized for Planck 857 GHz and Akari data were duplicated here. Source pixels are 90" for all bands, so an additional factor of $90^2 = 8100$ is included to restore energy scaling altered by SWarp. Input factors and final conversion factors are summarized in Table 5.13. Again, see Eq. 5.6 for a representative calculation.

Fortuitously, the entire Rosette Nebula fell onto single IRAS frames so no mosaic processing was required. As with other data, SWarp was utilized to resample the
Table 5.12: Combined flux uncertainties in the IRIS data determined by combining known factors in quadrature from [5].

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\lambda$ ($\mu$m)</th>
<th>Flux Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAS 1</td>
<td>12</td>
<td>11.2%</td>
</tr>
<tr>
<td>IRAS 2</td>
<td>24</td>
<td>5.8%</td>
</tr>
<tr>
<td>IRAS 3</td>
<td>60</td>
<td>11.2%</td>
</tr>
<tr>
<td>IRAS 4</td>
<td>100</td>
<td>7.8%</td>
</tr>
</tbody>
</table>

Table 5.13: Factors involved in converting IRAS data to W m$^{-2}$ arcsec$^{-2}$ in the data cube. Bandwidth and other input data from [5].

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\lambda$ ($\mu$m)</th>
<th>$\nu$ (THz)</th>
<th>$\Delta\nu$ (THz)</th>
<th>for W m$^{-2}$ arcsec$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAS 1</td>
<td>12</td>
<td>25.0</td>
<td>15.28</td>
<td>$2.9091 \times 10^{-14}$</td>
</tr>
<tr>
<td>IRAS 2</td>
<td>24</td>
<td>12.5</td>
<td>5.785</td>
<td>$1.1014 \times 10^{-14}$</td>
</tr>
<tr>
<td>IRAS 3</td>
<td>60</td>
<td>5.00</td>
<td>3.747</td>
<td>$7.1337 \times 10^{-15}$</td>
</tr>
<tr>
<td>IRAS 4</td>
<td>100</td>
<td>3.00</td>
<td>1.114</td>
<td>$2.1209 \times 10^{-15}$</td>
</tr>
</tbody>
</table>

source data to the standard resolution and dimensions for the data cube. A script was employed to multiply through the final conversion factor to produce data cube compatible maps, shown in Figure 5.6.

5.6 Midcourse Space Experiment (MSX) Observations

The Midcourse Space Experiment (MSX) completed multiple targeted surveys in near and mid-infrared bands. One of the specifically targeted regions for the mission was the Rosette Nebula, and as noted in the introduction several of the questions posed by those observations inspired this project. Because the Rosette was specifically targeted, MSX observed the entire Rosette in a single field on each of its four bands. The targeted Rosette results had better signal-to-noise than the more general sky survey conducted by the instrument, and provide the highest resolution 8 and 15 $\mu$m complete surveys of the Rosette region publicly available.

The telescope on Midcourse, named SPIRIT III, consisted of a clear aperture off-axis telescope with an effective 33 cm aperture paired with eight columns of Si:As blocked impurity band (BIB) focal plane detectors with 18.3” square pixels. Ultimately infrared light was collected in four bands in the Rosette region: 8.28 $\mu$m (A), 12.13 $\mu$m (C), 14.65 $\mu$m (D), and 21.34 $\mu$m (E). A band sensitivities were roughly 0.1 Jy, C and D band sensitivities were roughly 1 Jy, and E band sensitivities were between 2 and 6 Jy. Precision in the source data was 2-3%, with absolute photometric
Figure 5.6: IRAS flux calibrated energy maps of the Rosette region in data cube format. Bands: 12 µm, 24 µm, 60 µm, and 100 µm. Each frame displayed on individual square root flux scales.
accuracies of 5%, 3%, 4%, and 6% for bands A, C, D, and E respectively [126].

Calibrated source data were retrieved through IRSA and provided in energy units of \(\text{W m}^{-2} \text{sr}^{-1}\) with a \(1 \times 10^6\) multiplier included to manage astrometry. All bands had a 6" pixel size in the final data release, so a factor of 36 was divided out when SWarp was used to resample to a 1 arcsecond pixel that had to be manually restored. Translating to \(\text{W m}^{-2} \text{arcsec}^{-2}\) simply required multiplying the signal by \(1 \times 10^{-6}\) to remove the astrometry factor, 36 to remove the SWarp scaling, and \(2.35044 \times 10^{-11}\) steradian per arcsec\(^2\) to get a standard conversion factor usable across all four bands, specifically

\[
1 \times 10^{-6} \cdot 36 \cdot 2.35044 \times 10^{-11} \text{ sr/arcsec}^2 = 8.461584 \times 10^{-16} \text{ for final units in W m}^{-2} \text{arcsec}^{-2}.
\]

(5.8)

Scripting multiplied each resampled pixel by this value to create a data cube compatible frames in all four bands. Images of the resulting data cube slices are shown in Figure 5.7.

### 5.7 Wide-field Infrared Survey Explorer (WISE) Observations

The Wide-field Infrared Survey Explorer (WISE) surveyed the Rosette region in 2010, with the final, fully processed ALLWISE all-sky catalog released in November 2013. WISE mapped the entire Rosette region across four infrared bands centered at wavelengths of 3.4 \(\mu\text{m}\) (W1), 4.6 \(\mu\text{m}\) (W2), 12 \(\mu\text{m}\) (W3), and 22 \(\mu\text{m}\) (W4). These observations represent the highest resolution whole-nebula maps currently available in near and mid infrared bands, with median pixel scales of 2.76" in the shorter wavelength bands and 5.5" in the W4 band [170].

The primary optics were an afocal 40 cm diameter telescope comprised of six gold-coated mirrors, creating a parallel beam fed to the detectors. The shorter wavelength W1 and W2 bands utilized HgCdTe detector arrays while the longer wavelength W3 and W4 bands utilized Si:As BIB arrays [170]. These detectors had a high inherent photometric stability, and the source data provided in the final ALLWISE processing was calibrated in magnitudes using only the instrumental zero point. Overall systematic uncertainties of approximately 1.5% in W1, W2, and W3 and 1.8% for W4 are documented for a zero magnitude source [72].

Background subtraction and other processing for the ALLWISE survey was handled in large spatial “tiles,” with uniformity within tiles prioritized. Unfortunately, the Rosette Nebula lies at the intersection of four of these tiles, resulting in visible non-uniformity in the background when the ALLWISE observations are processed into mosaics with SWarp. Nevertheless, stars in overlap fields were checked and it was found that the observed signal was essentially consistent across the different tiles.

While the source data were calibrated in magnitudes, ALLWISE documentation provided a direct translation from source counts to Jansky for each filter, along with bandwidth information [72]. Once counts were translated to Jansky using this known factor, we multiplied by the known \(10^{-26}\) W m\(^{-2}\) Hz\(^{-1}\) per Jansky factor and multiplied by the documented bandwidth to retrieve a conversion factor to \(\text{W m}^{-2} \text{arcsec}^{-2}\).
Figure 5.7: MSX flux calibrated energy maps of the Rosette region in data cube format. Bands with mean wavelengths: A (8 µm), C (12 µm), D (16 µm), and E (24 µm). Each frame displayed on individual square root flux scales.
Table 5.14: Factors involved in converting WISE data to W m$^{-2}$ arcsec$^{-2}$ in the data cube. Filter information and Jy/count from [72].

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\lambda$ (µm)</th>
<th>Jy/count</th>
<th>$\Delta\nu$ (THz)</th>
<th>for W m$^{-2}$ pix$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>3.4</td>
<td>$1.9350 \times 10^{-6}$</td>
<td>17.506</td>
<td>$3.3874 \times 10^{-19}$</td>
</tr>
<tr>
<td>W2</td>
<td>4.6</td>
<td>$2.7048 \times 10^{-6}$</td>
<td>14.653</td>
<td>$3.9633 \times 10^{-19}$</td>
</tr>
<tr>
<td>W3</td>
<td>12</td>
<td>$1.8356 \times 10^{-6}$</td>
<td>11.327</td>
<td>$2.0758 \times 10^{-19}$</td>
</tr>
<tr>
<td>W4</td>
<td>22</td>
<td>$5.2269 \times 10^{-5}$</td>
<td>2.4961</td>
<td>$1.3047 \times 10^{-18}$</td>
</tr>
</tbody>
</table>

Final conversion factors are shown in Table 5.14. An example calculation for the W1 filter is shown below in Eq. 5.9.

$$1.9350 \times 10^{-6} \text{ Jy/count} \cdot 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ per Jy} \cdot 88.235 \times 10^{12} \text{ Hz} = 3.3874 \times 10^{-19} \text{ for final units of W m}^{-2} \text{ pix}^{-1}$$ (5.9)

SWarp was again used to resample to appropriate dimensions and pixel scale and the final conversion factor applied to produce flux calibrated data cube slices. Note that pixels in the ALLWISE source files were 1.37$''$ square, but because there is no solid angle dependence in the units used in the source data, SWarp correctly rescales by dividing out an area ratio of $1.37^2 = 1.877$, no manual correction is needed here. Flux scaling in the final resampled data cube frames was verified to be the same as in the original ALLWISE source data.

5.8 Wide-field FSQ Observations - Final Units and Scaling

At the end of the flux calibration described previously, FSQ wide-field data were in photons/s per pixel. Each pixel in these frames was 4.67 arcsecond square. In order to bring the wide field frames to the new standard, SWarp was again employed to resample the data to a scale of 1 arcsecond per pixel and limit the included region to the specified 2 x 2 field. The resulting signal reduction per pixel was handled internally by SWarp, with the result being values of photons/s per arcsec$^2$ in the new frames. To translate these values to the desired W m$^{-2}$ per pixel it was necessary to divide out the collection area of the FSQ and to account for the mean energy of the photon for each filter as shown in Table 5.15.

A script was employed to multiply each resampled pixel value by the combined factor to generate final master frames with values in W/m$^2$ per pixel.

As a check of both the flux calibration and unit conversion, the H$\alpha$ flux in the data cube slice may be compared to previous estimates. Celnik published an absolute flux calibration of the Rosette nebula in 1983, which has been regularly cited in the literature, showing a peak signal on his low spatial resolution map of $6.25 \times 10^{-18}$ W m$^{-2}$ arcsec$^2$ [24]. This compares favorably to the data cube H$\alpha$ signal, which shows
Figure 5.8: WISE flux calibrated energy maps of the Rosette region in data cube format. Filters with mean wavelengths: W1 (3.4 $\mu$m), W2 (4.6 $\mu$m), W3 (12 $\mu$m) and W4 (22 $\mu$m). Background brightness inconsistency is an artifact of calibration by the WISE collaboration. The bright, anomalous streak in the NW quadrant of the W3 and W4 slices appears to be a stray light artifact. Each frame displayed on individual square root flux scales.
Figure 5.9: Final data cube version of our flux calibrated, wide field, narrow band data taken with the FSQ instrument at Moore Observatory. Filters and mean wavelengths: [SII] (672.3 nm), Hα (656.4 nm), [OIII] (500.8 nm), and Hβ (486.3 nm). Each frame displayed on individual square root flux scales.
Table 5.15: Summary of factors used in bringing flux calibrated FSQ maps to the data cube standard W/m$^2$ per pixel. Energies per photon correspond to the center wavelength of the passband for each filter.

<table>
<thead>
<tr>
<th>Filter</th>
<th>J/photon</th>
<th>Area Correction (m$^{-2}$)</th>
<th>Combined Factor (J/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$\alpha$</td>
<td>$3.0281\times10^{-19}$</td>
<td>$1.1347\times10^{2}$</td>
<td>$3.4360\times10^{-17}$</td>
</tr>
<tr>
<td>H$\beta$</td>
<td>$4.0879\times10^{-19}$</td>
<td>$1.1347\times10^{2}$</td>
<td>$4.6385\times10^{-17}$</td>
</tr>
<tr>
<td>[OIII]</td>
<td>$3.9691\times10^{-19}$</td>
<td>$1.1347\times10^{2}$</td>
<td>$4.5037\times10^{-17}$</td>
</tr>
<tr>
<td>[SII]</td>
<td>$2.9567\times10^{-19}$</td>
<td>$1.1347\times10^{2}$</td>
<td>$3.3550\times10^{-17}$</td>
</tr>
</tbody>
</table>

a sharp peak in emission of $9.2\times10^{-18}$ W m$^{-2}$ arcsec$^2$ rapidly falling to a value just off-peak of $6\times10^{-18}$ W m$^{-2}$ arcsec$^2$.

5.9 Galactic Evolution Explorer (GALEX) Observations

The Galaxy Evolution Explorer (GALEX) launched in 2003 and completed a variety of surveys in near and far ultraviolet bands over its lifetime. The satellite utilized a 50 cm diameter, 3 m focal length modified Ritchey-Chretien telescope coupled to a dichroic beam splitter and sealed tube microchannel plate detector system to simultaneously observe the sky in far ultra-violet (135 - 175 nm) and near ultra-violet (175-280 nm) bands [94].

While the primary mission goals of the spacecraft were specific to extra-galactic astronomy, publicly available published data from the mission includes a complete survey of the Rosette Nebula region in the near ultraviolet band from 175 to 275 nm obtained through the Mikulski Archive for Space Telescopes (MAST). The entire region was covered in three maps, which were combined with SWarp into a single mosaic frame for inclusion in the cube. In addition to capturing bright emission from the OB stars in NGC 2244, faint extended emission from the nebula itself is evident.

The original NUV data files were in counts/sec where one count corresponds to one detected photon for the corresponding bandpass. Per GALEX documentation this corresponds to $2.06\times10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ per photon, and therefore per count [101]. To convert to the desired W m$^{-2}$ per pixel, we multiplied by $1\times10^4$ to convert to m$^2$, $1\times10^{-7}$ to convert to Watts, and 1050 Å for the bandwidth, for a combined factor of $2.163\times10^{-16}$ multiplied by the counts per second in the resampled file. The data were then resampled to the desired 1 arcsecond pixel scale and 2 degree region, and a factor of 0.4444 applied by SWarp to account for resampling from the default MAST pixel size. The resulting map is shown in Figure 5.48.

GALEX photometric precision is documented as ± 0.03 in absolute magnitude, which corresponds to ± 2.7% in absolute flux [101].
5.10 Conclusion

The final Rosette data cube consists of 38 slices of differing frequency and wavelength, ranging from the 21 cm emission line of neutral hydrogen (in the 1410 MHz band captured by the Effelsberg 100 m dish) to the near ultraviolet GALEX band centered at 227.1 nm in wavelength (1321 THz). Each slice has been resampled to the same oversampled 1 arcsec$^2$ pixel scale, spatially aligned, and placed on the same flux energy scale. It is therefore possible to look at any point within the nebula and easily compare flux across all available slices. Translation of this large volume of data to a mutually compatible standard was accomplished through the use of SWarp for spatial scaling and a variety of custom scripts to handle the needed rescaling in flux.

By including such a diverse multispectral dataset, we are able to perform a more comprehensive analysis of processes within the Rosette nebula, from free-free emission illustrated by the radio bands through thermal dust emission in IR and ionized gas line emission in the optical and ultraviolet. The interplay of these phenomena provide useful physical insight and constrain models of nebula dynamics and morphology.

In addition to providing a powerful tool for analysis of the Rosette across the included slices, establishing a consistent standard across this body of data also allows easy comparison to additional third party data. All data included in the cube covers the entire Rosette region, but partial maps of the region exist in a number of additional wavelengths and frequencies from missions such as Herschel and Spitzer in the infrared and CHANDRA in the x-ray regime. The standardized flux and spatial scales implemented in the cube can readily be applied to these additional sources as needed.

A montage of all data cube slices is shown in Figure 5.10 and each individual slice is shown in order of increasing frequency in Figures 5.11 through 5.48.
Figure 5.10: All data cube slices, with index numbers from Table 5.1 in order of increasing frequency. Each slice is shown on an individual square root flux scale.
Figure 5.11: Rosette Nebula data cube slice #1 - Mean frequency 1410 MHz, mean wavelength 21.27 cm, sourced from the Effelsberg 100 m radio telescope. Displayed on a square root scale from 0 to $1.97 \times 10^{-24}$ W/m$^2$ per square arcsecond. Original data from [25].
Figure 5.12: Rosette Nebula data cube slice #2 - Mean frequency 2700 MHz, mean wavelength 11.11 cm, sourced from the Effelsberg 100 m radio telescope. Displayed on a square root scale from $1.96 \times 10^{-25}$ to $1.44 \times 10^{-23}$ W/m$^2$ per square arcsecond. Original data from [55].
Figure 5.13: Rosette Nebula data cube slice #3 - Mean frequency 4750 MHz, mean wavelength 6.32 cm, sourced from the Effelsberg 100 m radio telescope. Displayed on a square root scale from 0 to $1.38 \times 10^{-22}$ W/m$^2$ per square arcsecond. Original data from [25].
Figure 5.14: Rosette Nebula data cube slice #4 - Mean frequency 22.80 GHz, mean wavelength 13.64 mm, sourced from Wilkinson Microwave Anisotropy Probe K band data. Displayed on a square root scale from 0 to $4.33 \times 10^{-22}$ W/m$^2$ per square arcsecond.
Figure 5.15: Rosette Nebula data cube slice #5 - Mean frequency 30.00 GHz, mean wavelength 10.00 mm, sourced from Planck data. Displayed on a square root scale from 0 to $3.82 \times 10^{-23}$ W/m$^2$ per square arcsecond.
Figure 5.16: Rosette Nebula data cube slice #6 - Mean frequency 33.00 GHz, mean wavelength 9.09 mm, sourced from Wilkinson Microwave Anisotropy Probe Ka band data. Displayed on a square root scale from 0 to $6.22 \times 10^{-22}$ W/m$^2$ per square arcsecond.
Figure 5.17: Rosette Nebula data cube slice #7 - Mean frequency 40.70 GHz, mean wavelength 7.50 mm, sourced from Wilkinson Microwave Anisotropy Probe Q band data. Displayed on a square root scale from 0 to $7.97 \times 10^{-22}$ W/m$^2$ per square arcsecond.
Figure 5.18: Rosette Nebula data cube slice #8 - Mean frequency 44.00 GHz, mean wavelength 6.82 mm, sourced from Planck data. Displayed on a square root scale from 0 to $1.71 \times 10^{-23}$ W/m² per square arcsecond.
Figure 5.19: Rosette Nebula data cube slice #9 - Mean frequency 60.80 GHz, mean wavelength 5.00 mm, sourced from Wilkinson Microwave Anisotropy Probe V band data. Displayed on a square root scale from 0 to \(1.59 \times 10^{-21}\) W/m\(^2\) per square arcsecond.
Figure 5.20: Rosette Nebula data cube slice #10 - Mean frequency 70.00 GHz, mean wavelength 4.29 mm, sourced from Planck data. Displayed on a square root scale from 0 to $1.57 \times 10^{-23}$ W/m² per square arcsecond.
Figure 5.21: Rosette Nebula data cube slice #11 - Mean frequency 93.50 GHz, mean wavelength 3.21 mm, sourced from Wilkinson Microwave Anisotropy Probe W band data. Displayed on a square root scale from 0 to $3.36 \times 10^{-21}$ W/m$^2$ per square arcsecond.
Figure 5.22: Rosette Nebula data cube slice #12 - Mean frequency 100.0 GHz, mean wavelength 3.00 mm, sourced from Planck data. Displayed on a square root scale from 0 to $2.67 \times 10^{-23}$ W/m$^2$ per square arcsecond.
Figure 5.23: Rosette Nebula data cube slice #13 - Mean frequency 143.0 GHz, mean wavelength 2.10 mm, sourced from Planck data. Displayed on a square root scale from 0 to $4.55 \times 10^{-23}$ W/m$^2$ per square arcsecond.
Figure 5.24: Rosette Nebula data cube slice #14 - Mean frequency 217.0 GHz, mean wavelength 1383 µm, sourced from Planck data. Displayed on a square root scale from 0 to $2.79 \times 10^{-22}$ W/m$^2$ per square arcsecond.
Figure 5.25: Rosette Nebula data cube slice #15 - Mean frequency 353.0 GHz, mean wavelength 849.9 µm, sourced from Planck data. Displayed on a square root scale from 0 to $3.10 \times 10^{-21}$ W/m² per square arcsecond.
Figure 5.26: Rosette Nebula data cube slice #16 - Mean frequency 545.0 GHz, mean wavelength 550.5 µm, sourced from Planck data. Displayed on a square root scale from 0 to $5.12 \times 10^{-18}$ W/m² per square arcsecond.
Figure 5.27: Rosette Nebula data cube slice #17 - Mean frequency 857.0 GHz, mean wavelength 350.1 µm, sourced from Planck data. Displayed on a square root scale from 0 to $2.17 \times 10^{-17}$ W/m$^2$ per square arcsecond.
Figure 5.28: Rosette Nebula data cube slice #18 - Mean frequency 1875 GHz, mean wavelength 160.0 µm, sourced from Akari N160 band data. Displayed on a square root scale from 0 to $1.02 \times 10^{-16}$ W/m² per square arcsecond.
Figure 5.29: Rosette Nebula data cube slice #19 - Mean frequency 2.14 THz, mean wavelength 140.0 µm, sourced from Akari WIDE-L band data. Displayed on a square root scale from 0 to $4.55 \times 10^{-16}$ W/m$^2$ per square arcsecond.
Figure 5.30: Rosette Nebula data cube slice #20 - Mean frequency 3.00 THz, mean wavelength 100.0 µm, sourced from IRIS reprocessed band 4 data from the Infrared Astronomical Satellite \[100\]. Displayed on a square root scale from $8.83 \times 10^{-18}$ to $1.47 \times 10^{-16}$ W/m² per square arcsecond.
Figure 5.31: Rosette Nebula data cube slice #21 - Mean frequency 3.33 THz, mean wavelength 90.0 µm, sourced from Akari WIDE-S band data. Displayed on a square root scale from 0 to $1.04 \times 10^{-16}$ W/m² per square arcsecond.
Figure 5.32: Rosette Nebula data cube slice #22 - Mean frequency 4.62 THz, mean wavelength 65.0 µm, sourced from Akari N60 band data. Displayed on a square root scale from 0 to $1.98 \times 10^{-16}$ W/m² per square arcsecond.
Figure 5.33: Rosette Nebula data cube slice #23 - Mean frequency 5.00 THz, mean wavelength 60.0 µm, sourced from IRIS reprocessed band 3 data from the Infrared Astronomical Satellite [100]. Displayed on a square root scale from $6.48 \times 10^{-18}$ to $2.36 \times 10^{-16}$ W/m² per square arcsecond.
Figure 5.34: Rosette Nebula data cube slice #24 - Mean frequency 12.50 THz, mean wavelength 24.0 \( \mu \)m, sourced from IRIS reprocessed band 2 data from the Infrared Astronomical Satellite [100]. Displayed on a square root scale from \( 8.06 \times 10^{-18} \) to \( 6.62 \times 10^{-17} \) W/m\(^2\) per square arcsecond.
Figure 5.35: Rosette Nebula data cube slice #25 - Mean frequency 13.63 THz, mean wavelength 22.0 µm, sourced from Wide-field Infrared Survey Explorer AllWISE survey W4 band data. Displayed on a square root scale from $1.27 \times 10^{-16}$ to $1.51 \times 10^{-16}$ W/m² per square arcsecond.
Figure 5.36: Rosette Nebula data cube slice #26 - Mean frequency 21.34 THz, mean wavelength 21.34 µm, sourced from Midcourse Space Experiment band E data. Displayed on a square root scale from 0 to $5.89 \times 10^{-17}$ W/m² per square arcsecond.
Figure 5.37: Rosette Nebula data cube slice #27 - Mean frequency 20.40 THz, mean wavelength 14.65 µm, sourced from Midcourse Space Experiment band D data. Displayed on a square root scale from 0 to $2.14 \times 10^{-17}$ W/m² per square arcsecond.
Figure 5.38: Rosette Nebula data cube slice #28 - Mean frequency 24.79 THz, mean wavelength 12.13 µm, sourced from Midcourse Space Experiment band C data. Displayed on a square root scale from 0 to 3.62 ×10⁻¹⁷ W/m² per square arcsecond.
Figure 5.39: Rosette Nebula data cube slice #29 - Mean frequency 25.00 THz, mean wavelength 12.0 \( \mu \text{m} \), sourced from IRIS reprocessed band 1 data from the Infrared Astronomical Satellite \cite{100}. Displayed on a square root scale from \( 1.03 \times 10^{-17} \) to \( 8.13 \times 10^{-17} \) W/m\(^2\) per square arcsecond.
Figure 5.40: Rosette Nebula data cube slice #30 - Mean frequency 25.00 THz, mean wavelength 12.0 µm, sourced from Wide-field Infrared Survey Explorer AllWISE survey W3 band data. Displayed on a square root scale from $6.74 \times 10^{-17}$ to $1.21 \times 10^{-16}$ W/m² per square arcsecond.
Figure 5.41: Rosette Nebula data cube slice #31 - Mean frequency 36.23 THz, mean wavelength 8.28 µm, sourced from Midcourse Space Experiment band A data. Displayed on a square root scale from $2.35 \times 10^{-18}$ to $7.57 \times 10^{-17}$ W/m² per square arcsecond.
Figure 5.42: Rosette Nebula data cube slice #32 - Mean frequency 65.22 THz, mean wavelength 4.60 μm, sourced from Wide-field Infrared Survey Explorer AllWISE survey W2 band data. Displayed on a square root scale from $3.13 \times 10^{-18}$ to $1.66 \times 10^{-17}$ W/m$^2$ per square arcsecond.
Figure 5.43: Rosette Nebula data cube slice #33 - Mean frequency 88.23 THz, mean wavelength 3.40 µm, sourced from Wide-field Infrared Survey Explorer AllWISE survey W1 band data. Displayed on a square root scale from $8.80 \times 10^{-19}$ to $2.37 \times 10^{-17}$ W/m² per square arcsecond.
Figure 5.44: Rosette Nebula data cube slice #34 - Mean frequency 446.2 THz, mean wavelength 672.3 nm, sourced from our own wide-field, narrow band observations using the FSQ instrument with the [SII] filter. Displayed on a square root scale from 0 to $1.10 \times 10^{-17}$ W/m$^2$ per square arcsecond.
Figure 5.45: Rosette Nebula data cube slice #35 - Mean frequency 457.0 THz, mean wavelength 656.4 nm, sourced from our own wide-field, narrow band observations using the FSQ instrument with the Hα filter. Displayed on a square root scale from 0 to $8.08 \times 10^{-18}$ W/m$^2$ per square arcsecond.
Figure 5.46: Rosette Nebula data cube slice #36 - Mean frequency 599.0 THz, mean wavelength 500.8 nm, sourced from our own wide-field, narrow band observations using the FSQ instrument with the [OIII] filter. Displayed on a square root scale from 0 to $5.28 \times 10^{-18}$ W/m$^2$ per square arcsecond.
Figure 5.47: Rosette Nebula data cube slice #37 - Mean frequency 616.9 THz, mean wavelength 486.3 nm, sourced from our own wide-field, narrow band observations using the FSQ instrument with the Hβ filter. Displayed on a square root scale from 0 to $3.59 \times 10^{-18}$ W/m² per square arcsecond.
Figure 5.48: Rosette Nebula data cube slice #38 - Mean frequency 1321 THz, mean wavelength 227.1 nm, sourced from Galactic Evolution Explorer near-ultraviolet band data. Displayed on a square root scale from 0 to $4.03 \times 10^{-17}$ W/m$^2$ per square arcsecond.

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Chapter 6 Extinction and Dust

The Rosette Nebula is a dusty object, and no physical analysis of the underlying processes of the gas can be successful without an understanding of the foreground extinction generated by this material. In an effort to quantify the impact of reddening and extinction due to this foreground dust, we undertook an analysis of this material and its impact using both the wide field atlas and the full range of available data cube slices.

6.1 Reddening

As a first step, it was necessary to determine the expected extinction for these narrow band wavelengths making use of Cardelli’s 1989 analysis of extinction over common photometric bands [18]. Starting from Table 3 on page 249, a graph of filter wavelength vs. \( A(\lambda)/A(V) \) (the magnitude of extinction normalized to \( A(V) \)) was generated and an Akima spline was used to create a continuous, interpolated curve, as shown in Figure 6.1. From this, we extracted values corresponding to the center wavelengths of the narrow band FSQ filters, as shown in Table 6.1.

A survey of the literature shows some uncertainty in the color excess for stars in NGC 2244. A diverse sampling was considered and an average taken from many sources, with values acquired by a multitude of methods [107], [114], [65], [112], [95], [13]. The resulting mean returns an approximate \( E(B-V) \) of 0.47, which suggests an \( A(V) \) of \( E(B-V) \times 3.1 = 1.46 \) utilizing the standard assumptions for dust composition and column density for pointings within the Milky Way [71]. With this value in hand, magnitude extinction differences were calculated for three filter ratios which were used for analysis of physical conditions within the nebula. Using the values from Table 6.1, \( \frac{A(\lambda_1)}{A(V)} - \frac{A(\lambda_2)}{A(V)} \) was determined for each ratio. Multiplying these values by the estimated \( A(V) \) to remove the normalization then returns \( A(\lambda_1) - A(\lambda_2) \), the magnitude difference. Finally, these magnitude results were converted to an

<table>
<thead>
<tr>
<th>Filter Band</th>
<th>Center (( \text{nm} ))</th>
<th>( A(\lambda)/A(V) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H( \alpha )</td>
<td>656.3</td>
<td>0.807</td>
</tr>
<tr>
<td>H( \beta )</td>
<td>486.1</td>
<td>1.193</td>
</tr>
<tr>
<td>[OIII]</td>
<td>500.7</td>
<td>1.145</td>
</tr>
<tr>
<td>[SII]</td>
<td>672.4</td>
<td>0.785</td>
</tr>
</tbody>
</table>

Table 6.1: Interpolated \( A(\lambda)/A(V) \) for Narrowband Filters
Figure 6.1: Plot and interpolation of normalized extinction as a function of center wavelength. Data from Table 3 of Cardelli 1989 [18].

The energy ratio was determined for each filter ratio, and the results are summarized in Table 6.2. The 0.596 ratio value cited for Hβ / Hα, for example, tells us that Hβ signal is reduced by a factor of 0.596 in energy compared to Hα due to interstellar reddening alone. To perform any physical analysis using this ratio, this factor must be included, either by dividing the Hβ / Hα by this factor or multiplying the inverse Hα / Hβ signal by that same factor.

### 6.2 Visual Extinction from the Hα/Hβ Ratio

As a check, this photon flux extinction ratio was applied to our measured Hα/Hβ ratio in the Rosette Nebula. A 36′′ radius circular region free of apparent dust centered at 6:31:18 +5:10:05 was selected and found to contain a mean measured energy ratio of 4.56. Using the results from Equation 6.2 we correct for anticipated foreground reddening by multiplying by a factor of 0.596, resulting in a measured energy ratio.
of 2.72. This corresponds well to the anticipated ratio of 2.89 for a typical 10,000 K hydrogen plasma calculated using case B assumptions \[44\].

Working the problem backwards, we can derive our own value for \(A(V)\) and, under standard conditions, \(E(B-V)\). Assuming a photon energy flux ratio of 2.89 for the unextincted region and comparing to the measured 4.56, we find an expected reddening correction in energy of \(2.89/4.56 = 0.634\). Following our previous calculation method backwards, this corresponds to an expected \(A(\lambda_1) - A(\lambda_2)\) of 0.495, which (assuming 0.386 for \(\frac{A(\lambda_1)}{A(V)} - \frac{A(\lambda_2)}{A(V)}\)) implied an \(A(V)\) of 1.28 and a corresponding \(E(B-V)\) of 1.28/3.1 = 0.414. This is slightly lower than other estimates, though it should be noted that all previously cited estimates of \(E(B-V)\) are from stellar measurements of the central cluster. It should also be noted that this estimate applies specifically to the least visibly extincted portion of the nebula, whereas the standard 0.47 is across the central cluster.

In order to better understand the \(V\)-band extinction across the object, a Python routine was constructed to apply this method pixel-by-pixel across the entire object. Using the final data cube version of the \(H\alpha/H\beta\) map as input and the \(\frac{A(\lambda_1)}{A(V)} - \frac{A(\lambda_2)}{A(V)}\) value from Table 6.2, an \(A(V)\) value was calculated for each pixel value (\(R\)) using the relation

\[
A(V) = \frac{-5}{2 \cdot 0.386} \cdot [\log_{10}(2.89) - \log_{10}(R)].
\]

We then selected a representative region within the central cluster, centered at 6:31:56 right ascension, +4:58:55 declination with a radius of 11.8’. The median \(A(V)\) value, to reduce the impact of stars, was found to be 1.52 across this region, which aligns very well with the previously stated mean value of 1.46 from studies of stellar \(E(B-V)\) in the literature. The \(A(V)\) map is shown in Figure 6.2.

With a spatial map of \(V\)-band extinction across the entire nebula, it was then possible to remove the effect of \(V\)-band extinction from images in optical bands. Because \(A(V)\) at each pixel was a known quantity, for any filter image we could retrieve the corresponding \(A(\lambda)/A(V)\) from Table 6.1 and use a Python script to multiply each pixel by this value to retrieve \(A(\lambda)\). The script then applied Eq. 6.1 for each pixel \(A(\lambda)\) value to produce a per-pixel factor analogous to the final column in Table 6.2. For each pixel of the original filter image, the scaled energy flux value
Figure 6.2: A plot of V-band extinction (A(V)) across the Rosette Nebula, derived from our flux calibrated H(α) / H(β) ratio map and reddening factors determined from Cardelli 1989 [18]. The map is shown on a square root scale from a minimum ratio value of zero to a maximum of 7.

is divided by this factor to produce an image with the extinction in the visible band removed. An example is shown in Figure 6.3.

A nearly identical procedure can remove visible extinction from ratio images of visible emission lines, using the \( \frac{A(\lambda_1)}{A(V)} - \frac{A(\lambda_2)}{A(V)} \) difference from Table 6.2 and multiplying by the A(V) in each pixel to produce \( A(\lambda_1) - A(\lambda_2) \), then applying 6.1 to get a factor map and proceeding as before. This process is used in a later analysis of the ionization state of the nebula.

Uncertainty in the final A(V) map derived here is entirely a function of uncertain-
ties in the flux calibrations of the original H\(\alpha\) and H\(\beta\) maps. As with those maps, uncertainty is primarily in the zero point, and the pixel-to-pixel variations seen in the A(V) map should be reliable to within the previously documented astrometric uncertainty of the original observations. Per the standard propagation of error formula for division in Eq. 6.3, and taking the worst case estimate of no covariance between the H\(\alpha\) and H\(\beta\) calibrations, we found a pixel to pixel zero point uncertainty for the ratio map \[10\]

\[
\sigma_f/f = \sqrt{\left(\frac{\sigma_{H\alpha}}{S_{H\alpha}}\right)^2 + \left(\frac{\sigma_{H\beta}}{S_{H\beta}}\right)^2 - 2 \frac{\sigma_{H\alpha H\beta}}{S_{H\alpha H\beta}}}.
\] (6.3)

Sigmas are standard uncertainties and S’s are intensities, therefore \(\frac{\sigma}{S}\) is given by the percentages previously documented in Table 4.6 and the final covariance term is taken to be zero. Substituting in we get a final worst-case uncertainty in the zero point of 14.28% in the ratio map. This is the uncertainty in the R value in Eq. 6.2, so it can be carried through that calculation using the standard propagation of uncertainty Eq. 6.4 to obtain a final magnitude uncertainty of \(\pm 0.155\) \[10\].

\[
\sigma_f = 2.5 \frac{\sigma_{H\alpha/H\beta}}{S_{H\alpha/H\beta} \cdot \ln(10)}
\] (6.4)
A much smaller uncertainty also exists in the canonical ratio for the Hα/Hβ ratio due to uncertainties about the electron temperature of the nebula.

### 6.3 Visual Extinction from the 21 cm/Hα Ratio

Extinction analysis using only our own visual data is limited by the spatial extent of the Hβ signal, as evidenced by the high frequency noise present in the final extinction map and derived data products. A deeper and more complete map is possible by combining our Hα data with the 1410 MHz (21 cm) radio data from the Effelsberg 100 m dish. This Effelsberg data is of such long wavelength that extinction is virtually non-existent along sight lines at distances of thousands of light years, allowing a full view of even those portions of the nebula rendered all but invisible by foreground dust [26]. By building a ratio of the 1410 MHz data to our own narrow-band Hα data, we produce a map where bright regions correspond to locations where light from Hα emission is blocked resulting in an artificially large ratio value.

The ratio of 21 cm HI emission to Hα emission is more temperature sensitive than the Hα to Hβ ratio used previously. Literature values for the electron temperature within the Rosette range from 8000 K to about 5000 K, with some proposing a temperature gradient which itself may be a function of foreground dust [40] [26]. As a first attempt, a temperature at the upper limits of the bound was selected to provide a representation of the electron temperature of the unobstructed gas. The expected emission in units of $4\pi j_\nu$ erg cm$^{-3}$ s$^{-1}$ for the 21 cm line and the Hα line were determined from a canonical model value for an 8000 K gas [44]. The predicted ratio of 1410 MHz to Hα emission is then a unitless value of $7.263 \times 10^{-8}$.

ALSVID scripts were used to divide the 1410 MHz data cube slice by the Hα slice to produce a ratio map. A Python script was then constructed to calculate A(V) from this ratio, as with the previous map derived from the visible hydrogen lines. In this case, the 1410 MHz map is taken to be without extinction, so the $A(\lambda)/A(V)$ for Hα alone from Table 6.1 was used. The resulting formula to be applied to each pixel, analogous to Eq. 6.2, is given by

$$A(V) = -\frac{5}{2 \cdot 0.807} \cdot \log_{10} \left( \frac{7.263 \times 10^{-8}}{R} \right). \quad (6.5)$$

The resulting map of V-band extinction is shown in figure 6.4.

Checking this A(V) map for comparison to the previous product, we find that the bright, largely unextincted region at 6:31:18 +5:10:05 returns a median A(V) of 1.36. This is reasonably close to the value returned from the Hα/Hβ derived A(V) map. Across the center of the nebula, however, there is greater divergence. Using the same 11.8′ radius region centered at 6:31:56 right ascension, 4: 58:55 declination, we find a median A(V) of 2.06, half a magnitude greater than in the optically derived map. This value is high relative to the typical values derived from stellar reddening in the literature, which range up to 1.7. It also appears slightly high relative to Celnik’s analysis of the extinction via the same method. Celnik’s derived V-band extinction ranged up to 2 or 3 magnitudes with distance from the central cluster, as ours does, but returned a slightly lower value in the central cluster itself, aligning with the higher
Figure 6.4: A plot of V-band extinction (A(V)) across the Rosette Nebula, derived from the flux calibrated 1410 MHz / H(α) ratio map and reddening factors determined from Cardelli 1989 [18]. The map is shown on a square root scale from a minimum ratio value of zero to a maximum of 7. Note that the Effelsberg 1410 MHz data had a half power beam width of 9.24 arcminutes, so detail below that level is oversampling from the Hα map. This map was used in the extinction correction of the [OIII]/[SII] map of the ionization parameter discussed later.
values cited from stellar observations of 1.6 or 1.7. It is likely this discrepancy is a product of his use of a 8000 K temperature for the baseline. It should be noted that this uncertainty in the electron temperature would impact the zero-point of this map only, but not the spatial distribution of extinction. In the future, other temperatures will be tested to see if a better fit can be attained between the radio-derived map and the purely optical map.

Using Eq. 6.3 and 6.4 along with the previously documented uncertainties of 4.19% for the \( \text{H}\alpha \) zero point and less than 1% for the 1410 MHz map we find a magnitude uncertainty on the order of \( \pm 0.047 \) for the magnitude zero point, but this range is misleading because the temperature dependence of the ratio is likely the larger uncertainty factor. In addition, the astrometric uncertainties noted previously for the interpolated radio data still apply to the radio derived \( A(V) \) map.

### 6.4 SED

In addition to its extinction impact on optical emission within and around the nebula, dust in HII regions can be observed and investigated by its thermal continuum emission in the infrared and microwave bands. Continuum emission from the dust dominates emission in these spectral bands, far exceeding that of thermal free-free and free-bound emission from the gas itself [44].

To investigate the distribution and physical parameters of dust in a region like the Rosette, it is common to utilize a spectral energy distribution (SED), a plot of flux vs. wavelength (or frequency) for a selected spatial region. With the complete and calibrated data cube it is possible to readily assemble a plot of this kind for any selected spatial region within the Rosette.

Four targets were ultimately selected for the SED, representing a diversity of physical conditions within the nebula. Each region was sampled by integrating over a 60 arcsecond radius circle centered at the specified coordinates. Figure 6.5 shows the regions sampled on both an optical and infrared map.

- A typical region of bright emission in the \( \text{H}\alpha \) frame, referred to in plots as “Bright Spot,” centered at right ascension 6:31:53 and declination +5:10:10, which contains no visible dust structures and appears flat in the extinction maps.

- A dark knot of dust in the \( \text{H}\alpha \) frame, referred to in plots as “Dark Cloud,” centered at right ascension 6:31:07 and declination +5:07:34, which is representative of dust knots contributing to foreground extinction in the optical nebula.

- The geometric center of the “Rogue Trunk” feature, centered at right ascension 6:31:58 and declination +4:58:05.

- A curious, bright, seemingly spherical “Ball” of emission only prominent in the 24 micron WISE frame (slice #25). This feature is centered at right ascension 6:34:48 and declination +4:54:23.
Figure 6.5: SED target regions within the Rosette, displayed against the Hα map (left) and the 24 µm emission map (right). Cumulative flux across each circle was sampled.

In order to determine the temperature of the dust in these regions, the SED must be fit to a thermal emission curve or curves. The fitting function we used is based on an optically thin modified blackbody. A true black body absorbs all incident radiation and emits thermal continuum according to the Planck function [71].

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$  \hspace{1cm} (6.6)

However, dust does not behave like a true black body, as some radiation is reflected. As a result, a modified black body curve is used to account for these effects. A detailed understanding of dust emission and absorption requires accounting for a diversity of factors including composition and grain size. To get a general idea of dust temperature, however, we can utilize a generic fitting function used by the Planck consortium,

$$I_\nu = \tau_{\nu_0} \cdot \left(\frac{\nu}{\nu_0}\right)^\beta \cdot B_\nu(T).$$  \hspace{1cm} (6.7)

Here, $I_\nu$, $\tau_{\nu_0}$ is the optical depth at frequency $\nu_0$, $\beta$ is the spectral emissivity index, and $B_\nu(T)$ is the Planck function [119]. In keeping with assumptions from Planck studies for generic dust clouds, a spectral emissivity index value of $\beta = 1.5$ was adopted for all wavelengths greater than 250 µm and $\beta$ was taken to be unity below this wavelength. These are typical assumptions based on extragalactic surveys [123].

A Python script was written to generate thermal dust curves according to this model, and curves for 30 K, 100 K, and 300 K were generated with arbitrary scaling but fixed frequency dependence. These curves were then fit to the existing SED. The
SED of selected targets is shown with these temperature curves in Figure 6.6 on a logarithmic scale.

The continuum dust emission between 250 and 3000 \( \mu m \) appears to be well-fit by the 30 K temperature curve, evidencing very cold dust. This is consistent with a shell of dust at a significant distance from the central ionizing stars. Thermal continuum emission at all four locations seems to be very consistent across this wavelength range, possibly implying a shell of relatively uniform, large grain dust across the foreground as suggested in Kraemer, Shipman et. al. [79].

Between 10 and 200 \( \mu m \), emission is better fit by the 100 K curve, implying this is emission by warmer dust closer to the central cluster. There is a broader variety of intensity values within the different regions in this spectral range, which may correspond to a less homogeneous distribution of material. However, some of the bands between 10 and 100 microns are strongly impacted by infrared emission lines from oxygen and PAH emission [44] as well as the prominent [CII] line at 158 \( \mu m \) [168]. Scattered starlight may also be a meaningful source of contamination at shorter wavelengths.
Figure 6.6: The spectral energy distribution of four target regions in the Rosette Nebula, presented on a logarithmic scale. Temperature curves assuming a spectral index of $\beta = 1.5$ for wavelengths about 250 $\mu$m and $\beta = 1$ below are also shown.
Chapter 7 Investigation of an Anomalous Feature

One elephant trunk structure, discussed earlier as a “rogue” trunk and not evident in absorption, occupies a distinctive location as shown in Fig. 7.1. It is likely in the foreground, along the line of sight to the central cluster, affording an unique opportunity to explore its chemistry through interstellar absorption line diagnostics.

This object was initially identified in image data from the Midcourse Space Experiment [79] as anomalously bright at 14.7 and 21.3 microns compared to the other familiar elephant trunk features that are distinguished by their strong absorption of the H-alpha emission from the nebula. It was also recently detected in the WISE W4 (22 micron) band, where it appears distinctively in the composite of WISE W4 and W3 (12 micron) data with our H-alpha data shown in Figure 1. The trunk-like arc of 25 micron emission is within 2 arcminutes (1 pc projected on the distance of NGC 2244) of HD 46150, one of the O-stars of the cluster thought to excite the visible emission of the Rosette. This star’s radiation field could produce the observed IR emission through thermal equilibrium of the dust. While the mid-IR emission from the usual elephant trunks in the Rosette has been identified as coming from dust carriers, there are problems with this interpretation for the anomalous trunk, given its proximity to the star. In order to have been stable for the lifetime of HD 46150, the anomalous trunk would have to be very massive, and should contain molecular material. Alternatively, it may be a recently formed transient, or a foreground feature heated by an embedded star.

Since the bright star HD 46150 exhibits strong diffuse interstellar bands [49, 164, 167, 80], we expect that line-of-sight absorption spectroscopy would provide a unique opportunity to probe a cloud of dust and molecular gas in an environment being modeled for its detailed physical processes. Fortunately, there is one star bright enough for high resolution spectroscopy that appears to be at the edge of the anomalous trunk in the multi-spectral data cube. It is identified as GSC 00154-01819, a V 11.6 star identified as spectral type A that has not been studied previously, other than to note its association with the central cluster [165]. A finder chart for this star is shown in Fig. 7.2. HD 46150 is the much brighter V 7.78 magnitude star 1' 25" to the southwest. A hot O5V star within the Rosette, it exhibits Na D interstellar absorption, and several of the well-known DIB lines up to 7000 A.

High resolution spectra of stars in the neighborhood of the Rosette would reveal the interstellar cloud motions and composition along a critical central sight into the center of the Rosette Nebula, as well as interstellar absorption within it. Also, if the anomalous trunk is in front of the star, then the data will assist in identifying the nature of this unusual object. Of course the diffuse interstellar band phenomena remains a major puzzle of interstellar astrophysics, and the detection of DIBs in this object, combined with physical diagnostics of the environment, would also provide new clues to their origin.
Figure 7.1: Rosette Nebula surrounding NGC 2244. Blue: Hα; Green: WISE W3 (12 mμ); Red: WISE W4 (22 mμ).

7.1 Cluster membership

There have been several studies of the membership of stars in the Rosette Nebula Cluster NGC 2244 intended to distinguish foreground and background stars from those physically within a reasonable cluster boundary. Table 7.1 summarizes the conclusions for the star of interest. Without high resolution spectra, and with distances exceeding the precision of current parallax determinations, there are two tools available for determining cluster membership: proper motion and the relationships of star colors and magnitudes. The earliest precision proper motion measurements were compiled by van Schewick [161], including our target star within the cluster. Subsequently, Johnson [73] undertook photoelectric photometry and on that basis decided that the star was not a cluster member, presumably on the basis of a $V$ versus $B-V$ color magnitude diagram.

Ogura and Ishida [107] used three-color UBV photometry with both photoelectric and photographic observations to understand the color excess $E(B-V)$ and total-to-selective extinction ratio $R = A_V/E(B-V)$ given an apparently anomalous value of $R$ for NGC2244. They analyzed $P = V - R(B-V)$ versus $Q = (U-B) - X(B-V)$ where $X = E_{U-B}/E_{B-V}$, and adopted values of $E_{B-V} = 0.47$ and $X = 0.73$, leading to a best fit for $R = 3.2 \pm 0.2$ for the cluster. With that, they compare the extinction-free magnitude $P$ to the reddening-free color $Q$ to identify stars that are brighter and redder than expected for a zero-age main sequence cluster member. Their star 181 is
Figure 7.2: Finder chart for GSC 00154-01819. The 40′ field shown is from the Digital Sky Survey, and the target star is marked. The bright star to its south is HD 46150, an O5V star responsible for exciting the nebular emission.
not a cluster member on this basis, and is identified as a foreground star.

Berghöfer and Christian [8] also constructed a $V$ versus $B - V$ color magnitude diagram of NGC2244 in the course of their study of the X-ray properties of the cluster stars. From this they identified the pre-main sequence stars known to be active with strong X-ray and Hα emission. They make no specific note of their star 56 in the paper or the associated Table, other than to report the measurements of $B$ (12.28), $V$ (11.61), $R$ (11.01), $I$ (10.74) and Hα (11.15) magnitudes. However, their Fig. 6 illustrates a $V$ versus $B-V$ color magnitude diagram on which star 56 falls midway between the ZAMS for the lower and upper reddening limits of $E_{B-V} = 0.38$ and $E_{B-V} = 0.85$. On this basis the star would be a candidate for cluster membership.

In the same year, Park and Sung [112] also reported new UBVI and Hα photometry. Based on their data, they constructed color-magnitude diagrams of $V$ versus $V-I$, $B-V$, $U-B$, and Hα compared to zero age main sequence (ZAMS) relations. They also incorporated proper-motion data and spectral types that had previously been measured and found $E_{B-V} = 0.47 \pm 0.04$, $R_V = 3.2 \pm 0.2$, and a distance modulus $V_0 - M_V = 11.1$. This distance modulus thus yields a distance of 1.7 kiloparsecs to the cluster. They also did not single out their star 207 as distinctive, although plotted on their Fig. 8 of $I$ versus $V-I$ the star would be brighter and less red than most stars of the cluster. The star could, in this context, be either a bright star with mass in excess of $2.5 M_\odot$ in or near the cluster, or a fainter foreground star of solar mass. They do not assign a spectral type, but they do give a 0% probability for cluster membership, and a membership quality assessment of 10/10 based on proper motion.

Chen, de Grijs, and Zhao studied proper motions of the NGC 2244 field [28], identifying GSC 00154-01819 as star 88 in their catalog. The find a higher membership probability of 70% in their study, distinguished by a comprehensive analysis of the statistics of proper motion distributions.

Wang et al. [165] used Chandra to study the stellar population of NGC2244. They identified over 900 X-ray sources, and 77% of them had optical or near-infrared stellar counterparts. GSC 00154-01819 is star 429 in their main catalog which included $J$, $H$, and $K$ photometry. In their Fig. 6 of $J$ versus $J-H$ it falls among a few exceptionally bright stars slightly to the right (red) side of the ZAMS for B5V, and almost exactly on the 2 Myr isochrone for pre-main sequence stars. Thus their data suggest that the star is a cluster member, and is young, hot, and ideal source for our use.

### 7.2 Available stellar data

There are few public data on spectra of stars in NGC 2244, or on stars that are not cluster members but lie along the line of sight to the region. [131] [132] A dissertation on the cluster stars that is widely referenced [162] for low resolution spectra is not available to us, but published work based on it [66] [112] suggest that the star of interest to us here was not included. A search of the ESO archive as of December 15, 2015, showed a few nearby stars with echelle spectra in the visible and near-infrared identified in Table 7.2.
Table 7.1: NGC2244 Cluster Membership for GSC 00154-01819.

### Cluster Study Identifications

<table>
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<tr>
<td>Johnson (1962)</td>
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<td>Ogura and Ishida (1981)</td>
<td>OI NGC 2244 181</td>
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<tr>
<td>Berghöfer and Christian (2002)</td>
<td>BC 56</td>
</tr>
<tr>
<td>Park and Sung (2002)</td>
<td>PS 207</td>
</tr>
<tr>
<td>Chen, de Grijs, Zhao (2007)</td>
<td>CDZ 88</td>
</tr>
<tr>
<td>Wang et al. (2008)</td>
<td>WTF Main 429</td>
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### Cluster Membership

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### Notes

<sup>a</sup>Proper motion (PM); Color and magnitude (CM); Radial velocity (RV)

<sup>b</sup>Member (Y), non-member (N), or probability (0 - 1)
Table 7.2: Rosette region stars with archival spectra [49].

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<td>HD 46180</td>
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Notes

\[ a \text{Stellar targets search on December 15, 2015} \]
\[ b \text{Search box parameter 10'} \text{ on 2MASS J06315775+0457496} \]
\[ c \text{ICRS (J2000)} \]
\[ d \text{Park and Sung NGC 2244 catalog [112]} \]

Park and Sung [112] adopt a color excess ratio of $E_{U-B}/E_{B-V} = 0.72$ to find $E(B-V) = 0.47 \pm 0.04$ from 28 members of NGC 2244 brighter than $V = 14$. They consider differences in the color excess ratio found by other authors, and some differences in reddening across the cluster, and from their measurements find $E(V-I)/E(B-V) = 1.27 \pm 0.06$ for probable cluster members. From this they derive a total-to-selective extinction ratio $R_V = 3.1 \pm 0.2$. These values establish a distance modulus $V_0 - M_V = 11.1$ and a distance of 1.7 kpc to the cluster. The binary variable star V578 Mon in the Rosette has a somewhat smaller spectroscopic distance of $1.39 \pm 0.1$ kpc [65].

Table 7.3 summarizes the previously known information about the target of interest, GSC 00154-01819.

7.3 University College London Echelle Spectrograph

The University College London Echelle Spectrograph (UCLES) on the Anglo-Australian 3.9 meter telescope offers high resolution and broad wavelength coverage with stability and precision suitable for radial velocity and line profile measurements. [1] [43] [157]. In collaboration with Dr. Bradley Carter of the University of Southern Queensland, in January 2014 we submitted a service observing proposal to obtain spectra of GSC 00154-01819.

The request was for UCLES configured as for the Anglo-Australian Planet Search
Table 7.3: Archival data on GSC 00154-01819 [23].

<table>
<thead>
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<th>Common Identifications</th>
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<tr>
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<tr>
<td>Declination (Dec) +04° 57' 49.67'' ICRS (J2000)</td>
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<tr>
<td>Proper motion (RA) 3.412 ± 1.576 mas/year</td>
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<td>Proper motion (Dec) −13.231 ± 0.690 mas/year</td>
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<td>R 11.01</td>
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<tr>
<td>I 10.85</td>
</tr>
<tr>
<td>J 10.409 ± 0.024</td>
</tr>
<tr>
<td>H 10.131 ± 0.021</td>
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<td>K 10.076 ± 0.023</td>
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<table>
<thead>
<tr>
<th>Notes</th>
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<tr>
<td>&lt;sup&gt;a&lt;/sup&gt;Young stellar object candidate</td>
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</table>
but without an iodine cell. UCLES is installed in a stable controlled environment at the f/36 Coudé focus. For our work, it used the 31.6 groove/mm echelle grating set for a central wavelength of 6050 Å in the 94th echelle order, with the E2V CCD camera. This CCD has a 4096 \times 2048 array of 13.5 \mu m square pixels with the long dimension in the direction of dispersion, and orders separated across the short dimension. The 1 arcsecond slit projects to about 4 pixels on the detector in the dispersion direction. Perpendicular to the width of the slit, an aperture mask limits sky background and eliminates blending across orders, projecting on a scale of 0.16 arcseconds/pixel which are binned during acquisition 2:1 into the output data on a scale of 0.32 arcseconds/pixel. The spectrograph is designed to have overlapping orders, and it records the Balmer series H\alpha line in m = 86 and 87. In the 86th order the wavelength scale is nominally 0.0372 Å/pixel. The 4-pixel slit width thus limits the resolution to about 44,000 at H\alpha. While higher resolution can be obtained with a narrower slit, this is accompanied by a considerable loss of light in 1.5 arcsecond median seeing since the slit clips the point-spread function (PSF) in the telescope focal plane. In the orthogonal direction, the aperture mask also limits the light that would be detected from the field near the star. For our data, this is equivalent to ±5 pixels in the focal plane above and below the limits of the star’s PSF-widened spectrum. That is, the spectra show the star and a small sample of the nebula less than ±2′′ to either side of the stellar PSF.

Three 1200-second exposures on the star were requested for a total of 1 hour on the star based on the AAT’s exposure estimator to obtain a signal-to-noise ratio of 80, along with Th-Ar spectral and quartz lamp continuum calibrations. The proposal was positively reviewed and allocated time for the 2014-2015 observing season. Spectra were taken in February 2015.

A summary of the spectral data files provided by the observing run is in Table 7.4.

### 7.4 Reduction of the spectral data

The three spectra that were obtained had a total exposure time of 3600 seconds, sufficient to provide a high resolution spectrum of the star once they were calibrated in wavelength and combined into a single data set. File 23, one of the three raw images, is reproduced in a linear gray scale display in Fig. 7.3.

Note that there is overlap from one order to the next, such that the file contains complete wavelength coverage from below 4820 Å in the 118th order to above 8300 Å in the 68th order, including most regions useful for stellar classification, the strongest interstellar DIB lines, and the diagnostic Rosette nebular atomic emission lines. The spectra also include telluric absorption lines, including the O2 system that is obvious as a pattern across the lowest orders of the cross-dispersed spectrum, and airglow emission lines. Other images provide wavelength calibration from a Th-Ar hollow cathode lamp, flat fields from a hot tungsten continuum lamp with a quartz window, and bias frame to remove the baseline response of the detector. The reduction process requires us to

1. Correct all frames for bias
Table 7.4: Spectra of GSC 00154_01819 with the AAT UCLES from Program UC 208.

<table>
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<tr>
<td>Observatory Latitude</td>
</tr>
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<td>Observatory Longitude</td>
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<tr>
<td>Telescope</td>
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<td>Top end focal ratio</td>
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<td>Spectrograph</td>
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<td>Spectral image size</td>
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<table>
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<tbody>
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</tr>
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<table>
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</tr>
<tr>
<td>11-15</td>
</tr>
<tr>
<td>24</td>
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</table>
2. Divide science and wavelength calibration frames by the flat field

3. Extract the orders of the science frames

4. Identify the thorium-argon spectral lines

5. Perform a non-linear wavelength fit to the ThAr spectra order-by-order

6. Apply that fit to the science orders

7. Correct for systematics in flux from order extraction

8. Combine the resulting data into a single set

At that stage, the data sets for each science spectrum can be combined, sorted, resampled as needed, and precisely calibrated before extracting the information we need: identification of the stellar spectral type, rotation rate, elemental abundances, radial velocity, and if possible, associated nebular emission. Fortunately, this first step is largely automated by a standard reduction pipeline used for Doppler-Zeeman analysis and exoplanet measurements. The thorium-argon (Th-Ar) wavelength standards for UCLES can be identified from an atlas [134]. Current best wavelengths are available from a critical compilation of Lovis and Pepe [90] based on precision measurements and transition identification by Palmer and Engleman [111]. Th-Ar, along with iron-neon (Fe-Ne) [38] are the preferred laboratory references for high-precision spectroscopy. Unlike an in-line iodine (I$_2$) absorption cell [157], however, the light path for an emission source may differ sufficiently for systematic small wavelength shifts to propagate through to the analyzed stellar spectra. Given a preliminary wavelength calibration based on these references, refined wavelengths can be established.
from telluric standards. We note that the calibration is done in terms of wavelengths in standard air, as is conventional. Matthew Mengel of the University of Southern Queensland (USQ) ran the data through the USQ processing pipeline and returned the extracted spectra to us as linear files of wavelength (in air) and flux from each order of each science image.

As shown in Fig. 7.3, the cross-dispersed spectrum has high resolution in one direction (horizontally in the Figure, but the “y” axis of the original image), and low resolution to sort orders of interference in the other direction (vertically in the Figure, and “x” of the image). For an order \( m \), and first order wavelength \( \lambda_1(y) \), the wavelength at each position is \( \lambda_m(x, y) = \lambda_1(y)/m \). Consequently for adjacent orders \( m \pm 1 \) there may be overlapped sampling of the same wavelength at the ends of order \( m \). In the Figure the Na D lines appear at both the left and the right sides, and at a given \( x \) in order \( m \), orders \( m \pm 1 \) differ by \( \Delta \lambda = \lambda/m \). As a result within each science image there may be more than one sample taken at the same wavelength. The resulting data files are non-uniform in wavelength sampling. The differences in wavelength for each multiply-sampled position preclude simply co-adding spectra, and each file may have from 3 to 6 separate measurements within the slit-limited spectral resolution at each meaningful spectral element. With a stable spectrograph and a precise Th-Ar calibration used for all science images, the instrumental wavelength shifts from one image to another are negligible. We combined the UCLES data from the three exposures into one sorted by wavelength.

These data were then resampled by interpolation on a linear mesh of 0.025 Å. This increment corresponds to a \( \Delta v \) in radial velocity of 1.25 km/s, and it does not degrade the pixel-limited resolution of the spectrograph in the regions of interest. To refine the wavelength calibration of the resampled spectrum, we used the Python Telfit package. Telfit employs the Line-By-Line Radiative Transfer Model (LBLRTM) and the HITRAN database to compute the absorption spectrum of Earth’s atmosphere. It identifies telluric lines in the stellar spectrum, shifts the stellar spectrum to match the air wavelength of the known telluric standards, and removes the telluric lines to produce a new clean spectrum on a precise wavelength scale that is largely free of absorption lines from Earth’s atmosphere. Telfit has been validated as an alternative for telluric standard star observations to correct for and remove telluric lines in near-infrared and optical stellar spectra. Its use of HITRAN, which is tied to laboratory spectra of major atmospheric constituents, accurately calibrates the stellar spectrum to geocentric standards on an absolute wavelength scale using the same light path as the star of interest.

Figure 7.4 compares the observed spectrum to the Telfit processed spectra. We note that Telfit identified the telluric lines correctly, and found a systematic shift between those standards and the Th-Ar calibration from the preliminary reduction of the UCLES data. Telfit also found a instrumental resolution of 44, 759 taken over the entire spectrum, and using that removed the atmospheric lines by modeling their contribution to the observed spectrum. The narrowness of the atmospheric lines is obvious in the Figure, and with instrumental broadening their contributions to the observed spectrum in the region shown are subtle but significant. Subsequent analysis uses the spectrum after Telfit processing with telluric lines removed and wavelength
7.5 Comparison to stellar spectrum models

The recent PHOENIX library of stellar high resolution synthetic spectrum models provides a reference for unambiguously determining the stellar spectrum type given a high resolution spectrum. [69] This physics-based self-consistent computation develops LTE (local thermodynamic equilibrium) model atmospheres with micro-turbulence, and includes elemental abundances, energy levels and transition probabilities in model spectra at a resolution of $R = \lambda/\Delta\lambda = 500,000$ for the optical and near-infrared. It uses more recent solar abundances than those of the Kurucz ATLAS9 [21][22] model, while generating spectra that agree with those of that lower resolution atlas. The PHOENIX spectra produce more accurate line shapes at high resolution. However, because PHOENIX uses synthetic spectra, some absorption lines present in the observed spectra are missing in its models, while they are present in the ATLAS9 model. This PHOENIX library has a grid of surface gravities
from log\((g) = -0.5\) to log\((g) = 4.0\) with LTE surface temperatures from 2300 K to 12,000 K, thus spanning the zero-age main sequence of spectral types of all but the hottest stars. Computed spectra are available in FITS data files that specify the LTE temperature, surface gravity (log\((g)\) in cm/s\(^2\)), metallicity (log\((\text{metals}/\text{H})\) relative to solar) and \(\alpha\)-element abundance enhancement. Since these are a self-consistent stellar models, the library parameters also include microturbulent velocities for LTE, molecular, and non-LTE lines (km/s), stellar mass (grams), stellar radius (cm), and stellar luminosity (erg/s).

To identify the spectral type, we compared the observed spectrum with telluric lines removed to the model spectra in this grid. Small differences in log\((g)\) and \(T_{\text{eff}}\) affect the shape and depth of lines in the Mg triplet region (5150 to 5120 Å), the Na D lines (5890 Å), and the H\(\alpha\) line (6563 Å) in distinctive ways. The dependence on \(\alpha\)-process element abundances affects the strength of lines selectively. We found that nearest best-fit grid spectrum was one with log\((g) = 4.5\), \(T_{\text{eff}} = 5800\), and solar metalicity and \(\alpha\). For reference the surface gravity of the Sun is \(2.74232 \times 10^4 \pm 7.9\) cm/s\(^2\), or log\((g) = 4.43\) cm/s\(^2\), and its LTE temperature is \(T_{\text{eff}} = 5771.8 \pm 0.7\) K. [113, 92] Since the grid spacing is 100 K in \(T_{\text{eff}}\) and 0.5 in log\((g)\), some additional refinement in the selection may be possible by interpolating the grid when higher signal-to-noise ratio spectra are available.

The stellar spectra in the PHOENIX model are computed with vacuum wavelengths, and without stellar rotation. Since the observed spectra are calibrated as wavelengths in air, it is necessary to convert back and forth between the two systems. Utilities in the PyAstronomy Library use the index of refraction of air computed with Edlen’s method to transform entire spectral files as needed. [128, 102, 48] We will work with vacuum wavelengths to determine the radial velocities by comparison to the PHOENIX model spectra.

We also have to broaden the PHOENIX model spectra to account for the rotation of the star. This is done with the PyAstronomy Library “rotBroad” function, which uses the Python Numpy library to convolve a rotational Doppler profile with the model stellar spectrum and generate a new model representing a rotating star of that type. The broadening function implements Gray’s method of treating the effect of stellar rotation on a spectrum dependent on two parameters, the line-of-sight equatorial surface velocity \(v\sin(i)\), and a linear limb-darkening coefficient \(\epsilon\). [20, 33, 130, 56] At low rotational velocities the effect of different limb-darkening models is small, and Diaz et al. [42] note that most authors use a fixed value of \(\epsilon\) in their analyses of rotational broadening. After confirming that the effect of \(\epsilon\) was not detectable, we also chose a fixed \(\epsilon = 0.5\) and compared rotationally broadened PHOENIX spectra to the observational data. The best fit was for \(v\sin(i) = 12.0 \pm 2\) km/s, which is to say a relatively slow rotator consistent with a late spectral type. Figure 7.5 shows similar models compared to the observed spectrum with nearby pixels resampled and averaged to reduce noise.

The Na D, Mg b, H\(\alpha\) and H\(\beta\) regions are sensitive to the spectral type and metalicity of the star. Figures 7.6 and 7.7 show the Na D lines with three different temperature model spectra, all with solar abundances and \(v\sin(i) = 12.0\). It is clear from this that \(T_{\text{eff}} = 5800\) K is a representative temperature, but different regions
Figure 7.5: The spectrum of GSC 00154-01819 with telluric lines removed compared to rotationally broadened PHOENIX models at $T_{\text{eff}} = 5800$ K with limb-darkening coefficient $\epsilon = 0.5$. Models with $\epsilon = 0.5 \pm 0.25$ cannot be distinguished from one another on this scale.

of the line fit better than others. Nevertheless, the fit to the theoretical spectrum is remarkably good and the temperature is certainly $T_{\text{eff}} = 5800 \pm 100$ K. Similarly, the Mg b region shown in Fig. 7.8 fits well for the same temperature range. Similarly, Figs. 7.9 and 7.10 show the first two lines of Balmer series and nearby Fe I lines. The H$\alpha$ spectrum also an emission component which is not from the star, but from the Rosette nebula summed over the slit aperture. The nebular emission will be discussed in Section 7.8 after we first extract the radial velocity from a comparison of the model and observed stellar spectra.

7.6 Radial Velocity

The comparison with model stellar spectra was done in a geocentric reference frame, that is with the star’s redshift due to its radial velocity removed. Given a precision wavelength calibration established from the telluric lines, and the identification of the star’s temperature so that an accurate template is known, we can now find the
apparent radial velocity of the star from the shift in the observed spectrum relative to the template. We used the PyAstronomy Library’s crosscorrRV routine with the Hα, Na D, and Mg b line region data as input to the template spectrum for $T_{\text{eff}} = 5800$ K. [128] This routine maximizes the correlation, and returns a topocentric radial velocity of the observed star. The results are shown in Table 7.5.

These are the velocities between the telescope and the star at the moment of the observation. They include the rotation of the Earth, Earth’s motion about the solar system barycenter, and the star’s motion relative to the barycenter. It is the later quantity that is of interest. The correction from topocentric to barycentric velocities is done with PyAstronomy Library’s “helcorr” routine. [128] As input the routine requires the longitude, latitude, altitude, Julian date and time of the observation. Also given the celestial coordinates of the target and the apparent topocentric radial velocity, it makes the geometrical and orbital computations to return the corresponding barycentric velocity. Taking each region separately, we find a mean topocentric velocity of $29.2 \pm 1.99$ km/s. The result for a cross-correlation of the entire spectrum is similar, $30.77 \pm 1.99$ km/s. The correction to the barycenter is $-16.42$ km/s, resulting in a barycentric radial velocity of $+14.4 \pm 2.0$ km/s for the entire spectrum, and
slightly lower at $+12.8 \pm 2.0$ km/s from the mean of the selected regions. HD 46150 identified in Fig. 7.2 as the bright star 1' 25" southwest of GSC 00154-01819 has a radial velocity of 31.83 ± 0.66 km/s. The cluster NGC 2244 has a mean radial velocity of 26.16 ± 3.37 km/s. Thus the radial velocity alone establishes that the star is not a cluster member, and that it is also probably not inside the Rosette Nebula.

### 7.7 AAT Results

The new spectroscopic data establish that GSC 00154-01819 is cooler, fainter, redder, and closer than we had anticipated based on the literature data shown in Table 7.3. The key piece of information is its effective temperature is 5800 ± 100 K. The PHOENIX models then provide the stellar mass, radius, and absolute luminosity. Pecaut and Mamajek [113] have used new observational data and the PHOENIX models to assign $T_{\text{eff}}$, intrinsic colors, and bolometric corrections to dwarf star spectral types O9 to M9, and based on that work we identify GSC 00154-01819 as spectral type G2V. Given its match to a spectrum with solar metalicity, it is a twin of the Sun.
Figure 7.8: The spectrum of GSC 00154-01819 with telluric lines removed in the region of the Mg b lines compared to rotationally broadened PHOENIX models.

The weight of the spectral evidence is apparent in the data shown in Figs. 7.11, 7.12, and 7.13 which compare the stellar spectrum to the Kurucz et al. solar flux spectrum with telluric lines. The solar spectrum has been broadened with a 12 km/s rotation to simulate an integrated-disk observation of a distant star.

The equivalence of these spectra, and particularly the close match on spectral line shapes, confirms that this is a main sequence G2V star. With the clear assignment of spectral type, we know the star’s intrinsic colors and absolute magnitude, and thus the obscuration by the local interstellar medium and its distance.

The $v \sin(i) = 12$ km/s rotation derived from the width of the stellar lines is informative of the rotation period, even with an unknown inclination $i$. If $i = 90^\circ$ and we are observing the star’s equatorial velocity, the rotation period is $P = 2\pi R_*/v$. For smaller inclinations as our view approaches pole-on, this apparent velocity is smaller than the equatorial velocity. Thus the assumption of an equatorial view gives the maximum $P$ consistent with an observed $v \sin(i)$, that is

$$P_* < 2\pi R_*/v \sin(i).$$

In a study of rotation periods of stars in NGC 6819 using the long time base of...
Kepler mission data, Meibom et al. [98] established a well-defined relationship between a star’s rotation period (from millimagnitude variation of its apparent magnitude), and its mass and color at the age of the cluster. This is a refinement and confirmation of method called gyrochronology in which the age of a star is determined from a measurement of its rotation. In his review of the determination of the ages of stars, Soderblom [150] concluded that for type G and K stars using the period \( P_\star \) is one of the better methods available to determine a star’s age. The method is tied to the spindown of stars through the “deterministic” coupling of their magnetic fields to the plasma in the star’s environment, that is, the age of a star of given type determines its rotation rate. Calibration of the relationship is through observations of clusters of known ages and theoretical models, and Soderblom recommends using the work of Mamajek and Hillenbrand [93] for F, G, and K stars. Similarly, the subsequent work of Meibom et al. [98] concludes that gychronology can provide an accurate age, with the caveat that for the youngest stars with ages less than about 300 million years there is a dispersion of rotation periods spanning two orders of magnitude. As stars age, the dispersion reduces rapidly and the gyrochronological ages converge by 600
Figure 7.10: The spectrum of GSC 00154-01819 with telluric lines removed in the region of the H$\beta$ line compared to rotationally broadened PHOENIX models.

For a star of solar radius, an equatorial rotational velocity of 12 km/s implies a rotational period of 4.2 days for the star. This short period would be detectable by ground-based photometry of a spotted or chromospherically active star, but there are no confirming observations reported as yet. The Sun’s slower differential rotation is well-established from observations of its spots, chromosphere, and corona, to have an equatorial sidereal period of 24.47 days. The long period and correspondingly slow surface velocity (2.07 km/s) are appropriate for its 4.6 billion year age. The much shorter period of GSC 00154-01819 is suggestive of youth. Indeed, Fig. 1 of Meibom et al shows a surface plot of the hypothetical relationship for period, age, and (B-V) colors of cool stars. On that diagram, this star would have less than the 600 million year gyrochronological age at which data are expected to be consistent. However, the calibration data given by Mamajek and Hillenbrand in their Fig. 9 show that a star with a 4.2 day rotation period and solar color would be in the same region as members of the Pleiades with an age of 130 million years.

Mamajek and Hillenbrand provide the calibration relationship based on 4 parameters: a, b, c, and n.
Table 7.5: Radial velocity of GSC 00154-01819.

<table>
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<tr>
<td>Na D</td>
<td>28.24 km/s</td>
</tr>
<tr>
<td>Mg b</td>
<td>31.52 km/s</td>
</tr>
<tr>
<td>Mean of regions</td>
<td>29.2 ± 2.0 km/s</td>
</tr>
<tr>
<td>Complete spectrum</td>
<td>30.77 ± 1.99 km/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barycentric Radial Velocity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Geocentric JD</td>
<td>2457056.94514</td>
</tr>
<tr>
<td>Heliocentric JD</td>
<td>2457056.94954</td>
</tr>
<tr>
<td>Target RA</td>
<td>97.99064168°</td>
</tr>
<tr>
<td>Target Declination</td>
<td>4.963797222°</td>
</tr>
<tr>
<td>Barycentric velocity toward the star</td>
<td>-16.42 km/s</td>
</tr>
<tr>
<td>Topocentric</td>
<td>30.77 ± 1.99 km/s</td>
</tr>
<tr>
<td>Barycentric correction</td>
<td>-16.42 km/s</td>
</tr>
<tr>
<td>Barycentric radial velocity</td>
<td>+14.35 ± 1.99 km/s</td>
</tr>
</tbody>
</table>

\[
P(B - V, t) = f(B - V)g(t) \tag{7.2}
\]
\[
f(B - V) = a((B - V)_0 - c)^b \tag{7.3}
\]
\[
g(t) = t^n \tag{7.4}
\]

For the age of the star \( t \) in millions of years, their revised gyrochronology parameters are \( a = 0.407 \pm 0.021 \), \( b = 0.325 \pm 0.024 \), \( c = 0.495 \pm 0.010 \), and \( n = 0.566 \pm 0.008 \). Thus there is a power law relationship between period and age which is color-dependent in the observational calibration, reflecting an initial mass-dependence in the underlying physical stellar development. With these values for a solar color \((B - V) = 0.65\), we find the star’s age \( t \) is 180 million years. Given \( P \) is an upper bound because of the unknown inclination \( i \), the star’s age from this method is also an upper bound.

The new observed and derived data are summarized in Tables 7.6 and 7.7. We note that the colors of the star match those of the G2V comparisons both in the BT-Settle model calculations based on the PHOENIX grid, and in the reference values
Table 7.6: New data on GSC 00154-01819.

<table>
<thead>
<tr>
<th>Spatial Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Ascension (RA)</td>
<td>06h 31m 57.754s ICRS (J2000)</td>
</tr>
<tr>
<td>Declination (Dec)</td>
<td>+04° 57′ 49.67″ ICRS (J2000)</td>
</tr>
<tr>
<td>Proper motion (RA)</td>
<td>3.412 ± 1.576 mas/year</td>
</tr>
<tr>
<td>Proper motion (Dec)</td>
<td>−13.231 ± 0.690 mas/year</td>
</tr>
<tr>
<td>Parallax</td>
<td>4.5 mas</td>
</tr>
<tr>
<td>Distance</td>
<td>219 parsecs</td>
</tr>
<tr>
<td>Radial Velocity</td>
<td>+14.35 ± 1.99 km/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stellar Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective temperature $T_{\text{eff}}$</td>
<td>5800 K</td>
</tr>
<tr>
<td>Spectral type</td>
<td>G2V</td>
</tr>
<tr>
<td>Metalicity</td>
<td>Solar</td>
</tr>
<tr>
<td>Rotation $v \sin(i)$</td>
<td>12 ± 2 km/s</td>
</tr>
<tr>
<td>Age</td>
<td>&lt; 180 million years</td>
</tr>
<tr>
<td>Radius</td>
<td>6.512 × 10$^5$ km</td>
</tr>
<tr>
<td>Mass</td>
<td>2.01 × 10$^{30}$ kg</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.42 × 10$^{26}$ W</td>
</tr>
<tr>
<td>Absolute magnitude $M_V$</td>
<td>4.862</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Photometric Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_V$</td>
<td>0.0</td>
</tr>
<tr>
<td>U</td>
<td>12.33$^a$</td>
</tr>
<tr>
<td>B</td>
<td>12.185$^a$</td>
</tr>
<tr>
<td>V</td>
<td>11.565$^a$</td>
</tr>
<tr>
<td>R</td>
<td>11.01$^{a,b}$</td>
</tr>
<tr>
<td>I</td>
<td>10.85$^a$</td>
</tr>
<tr>
<td>J</td>
<td>10.409 ± 0.024$^a$</td>
</tr>
<tr>
<td>H</td>
<td>10.131 ± 0.021$^a$</td>
</tr>
<tr>
<td>K</td>
<td>10.076 ± 0.023$^a$</td>
</tr>
</tbody>
</table>

Notes

$^a$Simbad [23]

$^b$RC ≈ 11.1 (This work)
Figure 7.11: The spectrum of GSC 00154-01819 with telluric lines removed in the region of the H\(\alpha\) line compared to rotationally broadened solar spectrum.

recommended by Pecaut and Mamajek [113] with one exception, the values of \(V_C - R_C\). Given that \(V_C\) enters into the other near-IR and IR colors, it appears likely that it is the value of \(R_C\) that is in error, and that it should be about 0.1 magnitude higher than listed by Simbad from Wang et. al’s Table 6 of available optical photometry. [23] [165]. Section 7.1 describes the sources of the data summarized by Wang, and it seems reasonable that there are unrecognized differences in the filters and data reductions of the various observers. A tentative revised value for \(R_C\) is indicated in Table 7.6. It does not bear on the following analysis. The value for \(B_C - V_C\) is 0.03 bluer than both the Sun’s reference color, and the models.

These comparisons suggest that GSC 00154-01819 is not significantly reddened, which would imply that it is within the low-reddening volume of the Local Bubble. [84] [83] However, Pecaut and Mamajek [113] note that recently formed stars are either far away (i.e. in this instance within the Rosette), or still in their birth molecular cloud. With the assumption of no reddening, we have an apparent \(m_V = 11.565\). This may be compared to reference absolute magnitude for this spectral type, \(M_V = 4.862\), to
establish a distance to the star. We have for a distance $d$ in parsecs,

$$m_V - M_V = 5 \log(d) - 5$$

$$d = 10^{\left(\frac{5 + m_V - M_V}{5}\right)}$$

With a distance modulus of $m_V - M_V = 6.703$, the star is 219 parsecs or 715 light-years from the Sun. A corresponding parallax of 4.5 milliarcseconds would have been delectable with Hipparcos but the star was not included in the catalog so there is no confirming parallax measurement. Since we use the absolute magnitude for a G2V solar star for finding the distance, it follows that the bolometric magnitude should be the same as the Sun, $M_{bol} = 4.7554$. The luminosity given in Table 7.6 is from the PHOENIX model for a 5800 K star and is 11% lower than the solar luminosity of $3.8270 \times 10^{26}$ W.

We note that because the star is not significantly reddened and is young, it is close to the zero-age main sequence and its spectrum should match that of the PHOENIX models closely. This is born out by the selected detailed comparisons shown here. Therefore, the spectral energy distribution of the star is known well enough for it to serve for flux calibration both for stellar photometry, and for wide field nebular
Figure 7.13: The spectrum of GSC 00154-01819 with telluric lines removed in the region of the Mg b lines compared to rotationally broadened solar spectrum.

mapping when the filter passbands used for those measurements are known. Although the spectra which were taken were not independently flux calibrated, the PHOENIX model also allows a relative flux calibration of the AAT spectral data so that line ratios of the background emission nebula can be found.

7.8 Nebular Spectrum

The spectra which were taken at the AAT record not only the star and the transmission spectrum of Earth’s atmosphere as we have discussed, but also emission from Earth’s atmosphere (airglow), and emission from the Rosette Nebula. These emission features are easily distinguished in the original FITS spectral images because they extend beyond the seeing disk of the star. While Balmer emission would be possible in some stars and appear within the stellar PSF, the spatial dimension of the spectra allow us to identify that the emission contributions we detect are non-stellar. Furthermore, atmospheric emission lines are very narrow, while those from the nebula are broadened by differential motions along the line of sight. Figure 7.14 shows the Hα region of one FITS science image. The spectrum extracted from all of the images
Table 7.7: GSC 00154-01819 colors.

<table>
<thead>
<tr>
<th>Color</th>
<th>Observed$^a$</th>
<th>BT-Settl Model$^b$</th>
<th>Intrinsic Reference$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_C - B_C$</td>
<td>0.145</td>
<td>0.201</td>
<td>0.133</td>
</tr>
<tr>
<td>$B_C - V_C$</td>
<td>0.620</td>
<td>0.674</td>
<td>0.650</td>
</tr>
<tr>
<td>$V_C - R_C$</td>
<td>0.465</td>
<td>0.726</td>
<td>0.363</td>
</tr>
<tr>
<td>$V_C - I$</td>
<td>0.715</td>
<td>0.726</td>
<td>0.713</td>
</tr>
<tr>
<td>$V_C - J$</td>
<td>1.156</td>
<td></td>
<td>1.197</td>
</tr>
<tr>
<td>$V_C - H$</td>
<td>1.434</td>
<td></td>
<td>1.491</td>
</tr>
<tr>
<td>$V_C - K$</td>
<td>1.489</td>
<td></td>
<td>1.564</td>
</tr>
</tbody>
</table>

Notes

$^a$ Johnson-Cousins colors from Simbad [23]
$^b$ Pecaut and Mamajek, Table 4 for $T_{eff} = 5800$ K and $\log(g) = 4.5 \, [cm/s^2]$ [113]
$^c$ Pecaut and Mamajek, Table 5 and Appendix C [113]

is seen in Figure 7.9.

Table 7.8 lists the brighter emission lines that should be in the Rosette spectrum, and the three bright forbidden night sky lines of [O I] that serve as benchmarks for emission detection. The Table does not list numerous lines of OH which are present at longer wavelengths because the spectra that were processed through the USQ pipeline did not include the low orders above 7000 Å. Because these are high resolution spectra, the signal/pixel is low and the possible useful data are limited to the few bright emission lines that are given in Table 7.8. To better identify lines of interest and confirm features that appear in the spectral plots, we re-processed the original FITS files through our own pipeline using ALSVID, the Python routines that were developed during this work. [76] Bias and flat frames were co-added with a median algorithm to eliminate cosmic ray events. The flat frames, which are spectra of a hot tungsten filament in a quartz envelope, were also bias subtracted and normalized. They reveal the interference fringing that affects spectra in very high orders, and also help to define the limits of the aperture mask that separates orders. Science frames are bias subtracted, and then co-added as sums to get the most data from the faint star. Coadding in this way leaves the cosmic ray events and uncorrected bright pixels in the final data, but they can be selectively removed for the lines of interest. Correction for flats can introduce a gradient (the tungsten lamp is much cooler than the star) and also add pattern noise. In low-flux spectra the primary uncertainty in flux at any pixel is the shot noise in the statistics of the detected photons, that is $\pm \sqrt{N}$ where $N$ is the number of detected photons. At an system gain of 1.3 photons
Figure 7.14: An unprocessed echelle spectrum of GSC 00154-01819. FITS science image 23 has been rotated 90° and transposed so that dispersion is horizontal with wavelength increasing to the right. Higher orders (longer wavelength) are at the top. The region around the Hα line in the 87th order is shown. The vertical dimension is angular displacement from the star, and the background Rosette nebula contributes at a greater radial velocity than the star’s.

per analog-to-digital unit (ADU), a digital “count” of 100 ADU is equivalent to 130 photons, with an uncertainty of ±11. At this noise level, flat field correction is not helpful and except for identifying orders we used only bias-subtracted spectra.

For each order of interest, the spectrum was rotated using spline interpolation so that select order ran parallel to a row, and rows sampling the star and the sky to either side were extracted and summed. These data for sky and star were then combined with the Telfit-calibrated spectra to confirm the identity, wavelength, and radial velocity of the features. The procedure introduces a wavelength uncertainty because the calibration must be transferred from the Telfit-processed stellar spectrum that runs through the center of the aperture to the nebular spectrum that is offset above and below center. The spectral lines in the echelle spectra are not precisely normal to the direction of dispersion, that is, they tilt slightly by an amount that increases with decreasing wavelength. This introduces a systematic error in addition to the uncertainty of matching the spectra which we estimate to be ±1 pixel in the dispersion direction, or about ±0.037 Å. That would be equivalent to ±1.7 km/s in velocity.

Figure 7.15 shows Hα and the stronger [NII] line at 6583 Å. The [NII] line at 6548 Å may also be discernable above noise, but there is a baseline that varies because of contamination of the stellar continuum and fitting this line would not yield useful data. The baseline in the Figure has been adjusted to remove a uniform background
Table 7.8: Potential emission lines in the spectrum of GSC 00154-01819.

<table>
<thead>
<tr>
<th>Potential Rosette Nebula Emission Lines$^{a,b}$</th>
<th>Source</th>
<th>Rest $\lambda_{air}$ Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>He I</td>
<td>7065.28</td>
<td></td>
</tr>
<tr>
<td>[S II]</td>
<td>6730.82</td>
<td></td>
</tr>
<tr>
<td>[S II]</td>
<td>6716.44</td>
<td></td>
</tr>
<tr>
<td>He I</td>
<td>6678.15</td>
<td></td>
</tr>
<tr>
<td>[N II]</td>
<td>6583.45</td>
<td></td>
</tr>
<tr>
<td>H$\alpha$</td>
<td>6562.801</td>
<td></td>
</tr>
<tr>
<td>[N II]</td>
<td>6548.05</td>
<td></td>
</tr>
<tr>
<td>He I</td>
<td>5875.67</td>
<td></td>
</tr>
<tr>
<td>[O III]</td>
<td>5006.843</td>
<td></td>
</tr>
<tr>
<td>[O III]</td>
<td>4958.911</td>
<td></td>
</tr>
<tr>
<td>He I</td>
<td>4921.93</td>
<td></td>
</tr>
<tr>
<td>H$\beta$</td>
<td>4861.363</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selected Atomic Airglow Lines$^{a,c}$</th>
<th>Source</th>
<th>Rest $\lambda_{air}$ Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O I]</td>
<td>6363.78</td>
<td></td>
</tr>
<tr>
<td>[O I]</td>
<td>6300.304</td>
<td></td>
</tr>
<tr>
<td>[O I]</td>
<td>5577.338</td>
<td></td>
</tr>
</tbody>
</table>

Notes

$^a$Osterbrock et al. [109]
$^b$SDSS [145]
$^c$Chamberlain [27]
that is probably scattered starlight, but possibly also moonlight since these spectra were taken during bright time with the Moon above the horizon. The removal was done by subtracting a $5^{th}$ order polynomial fit to the envelope and it works well for the regions under the primary lines. Gaussian fitting to these lines will also remove remaining background, so that the initial background removal is essentially cosmetic. Both strong lines are redshifted because of the Rosette’s radial velocity, and are broadened by differential structure within the spatial aperture. The signals could be quantitatively compared to the stellar continuum, but we do not know the stellar PSF and the light losses associated with that, so the resulting absolute calibration would be uncertain to a factor of 2 or more. In this instance, difference in instrumental response between [NII] at H$\alpha$ is not significant. For other lines, instrumental response can be removed by using the stellar continuum and the PHOENIX model standard. Values shown in the Figure are summed over three 1200 second exposures for a total of 3600 seconds exposure time.
dispersion direction. Consequently, the values are for an effective aperture of 0.32 square arcseconds wide. However, with 1.5 arcsecond seeing and only about 5 pixels useful to either side of the stellar spectrum, the data are also averaged over spatial region of the order of 3 arcseconds² for each spectral datapoint.

Fitting the Hα profile in the effective 3600 second total exposure with 0.32 arcsecond² spatial integration is

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height:</td>
<td>609.19 ± 11.62 photons/Å</td>
</tr>
<tr>
<td>Center:</td>
<td>6563.7282 ± 0.0108 Å</td>
</tr>
<tr>
<td>Width (1/e):</td>
<td>0.6911 ± 0.0153 Å</td>
</tr>
<tr>
<td>FWHM:</td>
<td>1.3549 ± 0.0301 Å</td>
</tr>
<tr>
<td>Area:</td>
<td>746.0 ± 30.8 photons</td>
</tr>
</tbody>
</table>

The topocentric radial velocity for the Rosette is 42.38 ± 0.49 km/s, with a 1/e velocity dispersion of 31.59 ± 0.70 km/s (or full width at half maximum of 61.94 ± 1.38 km/s). For the epoch of these observations the correction to be added to topocentric radial velocity to have barycentric velocity is -16.418 km/s, giving a barycentric radial velocity for the gas of 25.96 ± 0.49 km/s. The uncertainty given is for the fitting, to which for radial velocity we must add the uncertainty in wavelength calibration of ±1.7 km/s. Therefore the barycentric Hα radial velocity is 26.0 ± 2.4 km/s. This width and radial velocity are in agreement with values given from selected regions of the Rosette by Smith [147] using Fabry-Perot measurements, and of full widths of the order of 60 km/s measured by Fountain [51] near the center of the Rosette using an echelle.

For the stronger [N II] line at 6583 Å, also in the effective 3600 second total exposure with 0.32 arcsecond² spatial integration, we have

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height:</td>
<td>378.04 ± 18.9 photons/Å</td>
</tr>
<tr>
<td>Center:</td>
<td>6584.3574 ± 0.0253 Å</td>
</tr>
<tr>
<td>Width (1/e):</td>
<td>0.6207 ± 0.0359 Å</td>
</tr>
<tr>
<td>FWHM:</td>
<td>1.2175 ± 0.0703 Å</td>
</tr>
<tr>
<td>Area:</td>
<td>415.9 ± 44.8 photons</td>
</tr>
<tr>
<td>Relative photon flux S(N[II])/S(Hα):</td>
<td>0.558 ± 0.083</td>
</tr>
</tbody>
</table>

Given the precise rest wavelength of the [N II] line from the SDSS Table [145] as 6583.45 Å, the topocentric radial velocity is 41.3 km/s and the barycentric velocity is 24.9 ± 2.8 km/s with the uncertainty in the wavelength calibration added to the uncertainty in the fitting as we did for Hα. The [N II] 1/e velocity dispersion is 28.3 ± 1.6 km/s (full width at half maximum of 55.5 ± 3.2 km/s). Therefore, the
values of the radial velocity and the gas velocity dispersion for [N II] are close to those for Hα when measurement errors are taken into account. The ratio of flux in photons is \( S([N\text{II}])/S(H\alpha) = 0.56 \pm 0.08 \) given negligible change in instrument response over this wavelength range.

There is also a small but detectable signal in [S II] in the red, and in Hβ in the blue. For other lines in Table 7.3 the nebular emission is lost in the stellar scattered light and the sky background. For the Hβ line, in the 3600 second total effective exposure with 0.32 arcsecond\(^2\) spatial integration, we have

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>170.1 ± 31.2 photons/Å</td>
</tr>
<tr>
<td>Center</td>
<td>4862.311 ± 0.050 Å</td>
</tr>
<tr>
<td>Width (1/e)</td>
<td>0.3354 ± 0.0710 Å</td>
</tr>
<tr>
<td>FWHM</td>
<td>0.658 ± 0.139 Å</td>
</tr>
<tr>
<td>Area</td>
<td>101.1 ± 39.8 photons</td>
</tr>
<tr>
<td>Relative photon flux ( S(H\beta)/S(H\alpha) )</td>
<td>0.261 ± 0.113</td>
</tr>
</tbody>
</table>

The rest air wavelength of Hβ is 4861.363 Å, yielding a rather large barycentric radial velocity of 42.1 ± 6.4 km/s after a wavelength calibration uncertainty of 2 pixels is included. The Hβ 1/e velocity dispersion is 20.7 ± 4.4 km/s (full width at half maximum of 40.6 ± 8.6 km/s).

The total flux detected at Hβ in this spatial area can be compared to Hα if we take into account the instrumental response ratio over this wavelength range. For this, we can use the stellar flux itself because we know that the star is not reddened, we have the PHOENIX model of the star’s flux, and we can compare the same spatial cross section of the PSF at wavelengths near the Hβ and Hα lines. In this case, the stellar model ratio is \( F_\star(H\beta)/F_\star(H\alpha) = 1.39 \) in the continuum on the short wavelength side of both lines when the flux is measured in ergs/s/cm\(^2\)/Å at the star’s surface. Measured in photons rather than in energy (\( h\nu \)), we must multiply this by \( \lambda(H\beta)/\lambda(H\alpha) \) since it takes fewer photons at Hβ to have the equivalent energy at Hα. Thus the flux ratio in photons leaving the star is \( F_\star(H\beta)/F_\star(H\alpha) = 1.03 \). The measured continuum ratio in the UCLES data is \( C_\star(H\beta)/C_\star(H\alpha) = 0.534 \) when the same aperture is used on both echelle orders. Consequently, the instrument is less responsive at Hβ than at Hα by 0.534/1.03 = 0.518. With this calibration, the emission line ratio for the Balmer series in the Rosette is \( S(H\beta)/S(H\alpha) = (101.1/746.)/0.518 = 0.261 \pm 0.113 \). Or, the inverse ratio in photons is \( S(H\alpha)/S(H\beta) = 3.8 \pm 1.7 \). The uncertainty in the ratio is large primarily because of the noise in the measurement of the faint Hβ emission line profile.

Similarly, the two [S II] lines recorded in the 3600 second total effective exposure with 0.32 arcsecond\(^2\) spatial integration, we follow the same procedure to obtain
The spectroscopic properties of the nebula background close enough to the star to be seen in the slit are summarized in Table 7.9. The weaker [N II] was not measurable and is probably less than 20% the strength of the stronger 6583 line.
Table 7.9: Rosette Nebula Background at GSC 00154-01819.

<table>
<thead>
<tr>
<th>Line</th>
<th>$V_R$ km/s</th>
<th>$\sigma_V$ km/s</th>
<th>Relative Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>[S II] 6730.82 Å</td>
<td>26.702 ± 4.05</td>
<td>55.1 ± 11.2</td>
<td>0.114 ± 0.048</td>
</tr>
<tr>
<td>[S II] 6716.44 Å</td>
<td>31.3 ± 2.33</td>
<td>39.2 ± 6.4</td>
<td>0.122 ± 0.043</td>
</tr>
<tr>
<td>[N II] 6583.45 Å</td>
<td>24.9 ± 2.8</td>
<td>55.5 ± 3.2</td>
<td>0.56 ± 0.08</td>
</tr>
<tr>
<td>[N II] 6548.05 Å</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>H(\alpha) 6562.801 Å</td>
<td>26.0 ± 2.4</td>
<td>61.94 ± 1.38</td>
<td>1.0</td>
</tr>
<tr>
<td>H(\beta) 4861.363 Å</td>
<td>42.1 ± 6.4</td>
<td>40.6 ± 8.6</td>
<td>0.261 ± 0.113</td>
</tr>
</tbody>
</table>

Notes

Barycentric radial velocity $V_R$
HWHM velocity dispersion $\sigma_V$
Flux in photons relative to H\(\alpha\)
Chapter 8 Ionization

8.1 Excitation of Forbidden Lines

Forbidden line emission like that observed in the [OIII] and [SII] slices of the data cube is driven by a different process than hydrogen emission. Rather than recombination, these forbidden lines are generated by excitation driven by the kinetic energy of electron impacts on the ground state of the excited atom [47]. This necessarily reduces the ambient kinetic energy of the gas, cooling it. The resulting thermal energy loss is the primary cooling process in maintaining the thermal equilibrium of the nebula [44].

As in the case of hydrogen discussed earlier, we can reasonably make the assumption that any excitation takes place from the ground state. In this case, collision frequency is low and de-excitation is rapid. This means that energy is being rapidly redistributed throughout the gas, implying a unique temperature corresponding to the a particular distribution of particle energies [47].

If we call the ground state \( i \) and the excited state \( j \), the rate of collisional excitation from \( i \) to \( j \) \((N_{ij})\) depends on the ion density \((n_I)\), the electron density \(n_e\), the and a collision rate coefficient \(C_{ij}\) which is strongly dependent on the electron temperature \(T_e\).

\[
N_{ij} = n_e n_I C_{ij}(T_e) \tag{8.1}
\]

\(C_{ij}\) is in turn of the form

\[
C_{ij}(T_e) = (A_{ij}/T_e^{1/2}) \exp(-\phi_{ij}/kT_e) \tag{8.2}
\]

Here, \(A_{ij}\) is a constant depending on the ion and transition being considered [47].

Each excitation is followed by the emission of a photon of energy \(\phi_{ij}\), so the energy emitted per unit volume by this process \((L_{ij})\) is given by the following expression [47].

\[
L_{ij} = N_{ij}\phi_{ij} = n_e n_I C_{ij}(T_e)\phi_{ij} \tag{8.3}
\]

The distribution of forbidden line emission varies from species to species and transition to transition, as is very clear in slices 34 and 36 of the data cube pictured in Figures 5.46 and 5.44. These variations are a function of both the spatial distribution of the elements and the ionization potential of each. In general, a forbidden line corresponding to a more energetic ionization potential will tend to be found closer to the ionizing sources [17]. It is readily seen that the emission from doubly ionized oxygen ([OIII]) is more pronounced close to the central cluster, while the [SII] emission is more evenly distributed and extends out much further from the central cavity. A false color composite of the [SII] and [OIII] demonstrates this distribution even more clearly in Figure 8.1.
Figure 8.1: A false color composite of Rosette Nebula data cube slice #34 ([SII] in green) and #36 ([OIII] in blue). Both are shown on a linear scale from 0 to $2.6 \times 10^{-18}$ W/m$^2$ per square arcsecond. In red, thermal dust continuum at 8 microns from data cube slice #31 is shown for context. The dust continuum is presented on a linear scale from $2.35 \times 10^{-17}$ to $7.57 \times 10^{-17}$ W/m$^2$ per square arcsecond.
8.2 The Ionization Parameter

One effective diagnostic of the radiation field in a region such as the Rosette Nebula is the ionization parameter \((U)\).

\[
U = \frac{1}{4\pi r^2 \text{cn}_H} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu
\]  

(8.4)

Here, \(L_\nu\) is the luminosity of the ionizing source per unit frequency interval and \(r\) is the distance from the source. In physical terms, the ionization parameter is the dimensionless ratio of the ionizing photon density to the electron density in the gas \[44\].

Assuming a uniform distribution of oxygen and sulfur throughout the nebula, then, it is possible to map the ionization parameter by examining the ratio between the [OIII] and [SII] line emission. The spectrum of the exciting source is a constant, but the ionization energy required to doubly ionize oxygen is markedly higher than that needed to singly ionize sulfur. This difference in ionization potential means that a ratio of the two forbidden lines provides a spatial map of the ionization that should be directly proportional to the ionization parameter, barring saturation effects due to finite populations of the target elements \[173\]. Furthermore, [OIII] line emission is strongly temperature sensitive, and therefore serves as a proxy for ionizing flux. [SII] is density sensitive, in that it is temperature insensitive at low densities and therefore serves as a proxy for electron density. Again, the result is that the ratio [OIII]/[SII] is proportional to the ionization parameter \[163\].

Data cube slices 34 and 36 were used to construct such a map, and an ALSVID script \[76\] was used to divide one flux-calibrated frame from the other to produce a map of the flux ratio [OIII]/[SII]. Because both forbidden lines are in the optical, it was necessary to account for the impact of foreground extinction before other physical parameters could be assessed. Starting from the A(V) map derived previously from the comparison of H\(\alpha\) and 21 cm hydrogen emission, the same Python script used to generate the extinction-removed map in Figure 6.3 was applied to the [OIII]/[SII] map. From Table 6.2 the necessary reddening factor input is given by \(
\frac{A([\text{OIII}])}{A(\text{V})} - \frac{A([\text{SII}])}{A(\text{V})} = 1.145 - 0.785 = 0.360.
\)

For each pixel in the A(V) map, the pixel value is multiplied by this factor to produce the extinction in this ratio A([OIII]/[SII]). As in the previous extinction removal example, a Python script then applied Eq. 6.1 for each pixel’s A([OIII]/[SII]) value to produce a per-pixel factor analogous to the final column in Table 6.2. For each pixel of the original ratio image, the scaled energy value is divided by the resulting factor to produce an image with the extinction in the visible band removed. The resulting map showing the spatial variation in the ionization parameter across the nebula is shown in Figure 8.2. Again, the white speckling beyond the edges of the visible nebula is high frequency spatial noise resulting from a lack of signal in both bands.
Figure 8.2: An extinction corrected map of the [OIII]/[SII] forbidden line energy ratio, showing the spatial variation in the ionization parameter across the Rosette Nebula. Brighter pixels correspond to a larger ratio value, and therefore a larger ionization parameter. The ratio of energy flux is presented on a square root scale from 0 to 11.
8.3 Ionization Map Analysis

In a very general sense the map of the ionization parameter evidences a clear trend. Bearing in mind that whiter pixels correspond to larger ratio values, we find that the [OIII]/[SII] ratio, and therefore the ionization parameter, is greatest just outside the central cavity. There is a gradual decrease in ionization with increasing radius, with a sharp dark region of low ionization encircling most of the optical nebula. This general pattern corresponds well to the expected ionization stratification of [OIII] and [SII], wherein the species with the higher parent ionization potential is most prevalent nearer the ionizing sources [47]. There are significant regional differences across the object which should be considered, however.

The north eastern (upper left) quadrant of the Rosette Nebula is unusual, in that it is the only portion of the nebula not bounded by dust and the surrounding molecular cloud. This is evident in Figure 8.1 where the red dust cocoon does not enclose the north east extreme of the object. In the radio data (see Figure 5.11) there is an evident drop in emission, and consequently in presumed gas density, in this region. Based on the inverse ionization parameter dependence on gas density described in Equation 8.4, there should be an increase in ionization parameter in this region relative to radius. This relationship does hold for some time, as can be seen in Figure 8.2 with a finger of higher ionization extending toward the north east border. The ratio then rapidly drops into the surrounding noise, due to lack of signal from both gases as a result of the matter boundary of the nebula. There is, however, also a dark region of very low ionization parameter at the northern edge of the opening. It is likely that the Monoceros Loop supernova remnant is responsible for this effect. The expansion of the supernova into the nebula appears to be creating dense pressure shocks in this region, and this abrupt density increase would cause a corresponding sharp drop in the ionization parameter. The full impact of the supernova’s interaction with the nebula is poorly understood, and possible differences in elemental abundances and high energy radiation from the SNR may also contribute to the observed ionization parameter along the north eastern edge.

To the north and north west (upper right), the ionization appears to drop off sharply as the dust boundary with the nebula is approached. It is well documented that the interface between the molecular cloud and the expanding nebula is a region of turbulence and increased pressure [88]. It is reasonable to speculate that this boundary layer may also be a region of increased gas density, accounting for the very sharp decrease in ionization parameter in some border regions.

To the west, near the central cluster, vague traces of some of the denser elephant trunk structures are still apparent. This may be a product of dust scattering ionizing UV photons and thereby shielding small pockets of the gas.

The boundary compression effect noted earlier is not evident in the interface between the gas and dust in the south west (lower right), but this is readily explained by the interference of the foreground dust cloud and PDR. As is clear from a comparison of the optical slices (such as Figure 5.45) and the radio (such as Figure 5.11) a portion of the south eastern nebula is completely obscured by foreground dust. This is a bright white patch in the radio extinction map, Figure 6.4. Since no optical signal
from either forbidden line makes it through the foreground extinction, the extinction 
correction can not compensate, and there is consequently no information available in 
this map about the south west boundary with the molecular cloud.

To the east and south east (lower left) there is a great deal of structure in the 
spatial distribution of the ionization parameter. Twisting dark clouds which do not 
correspond to optical extinction are evident, and likely represent density variations 
in this turbulent region. The intersection with the molecular cloud on this side is 
one of the most active star formation regions in the nebula \cite{87} and it is reasonable 

to conclude that interacting of stellar winds and magnetic fields may be responsible 
for these unexpected dense areas, which somewhat resemble shock fronts. Ybarra 
et. al. attribute these filaments to pressure shocks due to young stellar objects at 
the nebula boundary, and note the presence of molecular outflows bright in [SII] 
in the region which would impact the structure of our ionization map \cite{172}. Also, 
this region is dotted with regions of intense ionization markedly stronger than at 
equivalent radius elsewhere. This implies that more local, newly formed stars may 
be contributing to forbidden line emission in this region. Some of the extended 
dust structures protruding from the eastern molecular cloud boundary also appear 
to exhibit the UV shielding effect discussed earlier, though again this does not (and 
should not) map exactly to the visual extinction.

Finally, the center of the nebula presents a puzzle. As is clear from Figure \ref{fig:8.1} 
[SII] emission is roughly constant across the entire face of the nebula, including the 
central cavity. By contrast, [OIII] emission is drastically reduced relative to the 
surrounding nebula, similar to the hydrogen emission. This difference may be due 
to an inhomogeneity in the distribution of sulfur and oxygen, but there is no clear 
reason why this inhomogeneity should exist. Instead, consider a shell of homogeneous 
O and S gas around a hollow central cavity. Assuming the same general pattern of 
decreasing ionization parameter with radius observed for the Rosette in the two-
dimensional case, the ionized sulfur in the foreground and background of the cavity 
would have considerably longer line of sight path lengths than the comparatively 
concentrated doubly ionized oxygen emission along that same column. This geometry 
might account for the apparent decrease [OIII], and therefore ionization parameter, 
across the center. This thick shell and evacuated cavity geometry is further discussed 
in the following chapters.

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As a step toward understanding the morphology of the nebula, an analysis utilizing the apparent radial symmetry of the object was undertaken. The nebula was parsed into a series of concentric rings, and the average emission from each of those rings as a function of distance from the center provided a radial profile of the object in each of the 38 data cube bandwidths. This radial profile was then analyzed via Abel inversion\[57\] to ascertain to what extent the observed emission could be modeled on the assumptions of cylindrical or spherical symmetry.

9.1 Masking

In order to study the plasma and dust emission it was necessary first to isolate the diffuse emission from the significant point source contributions due to bright stars in the region. To this end, a Python script was constructed to generate a “star mask,” a map of regions which would be excluded from the radial profile averages. The mask itself was produced by looking at individual data cube slices and choosing a threshold value above which only emission from bright stars was present. The script then marked any pixels above that threshold as part of the mask. Because different stellar sources have peak emission at different wavelengths, it was necessary to build threshold maps for many of the data cube slices and combine them to form a final, comprehensive star mask for the region. No point source contributions appear beyond the infrared, so only UV, optical, and infrared frames were included in star mask construction. Table 9.1 summarizes the data cube slices and threshold values used to make the final star mask.

The final mask is an array 7200 x 7200 pixels with identical pixel scale and WCS to the data cube frames themselves. It consists only of 1’s and 0’s, where 1 indicates

<table>
<thead>
<tr>
<th>Data Cube Index</th>
<th>Slice Identifier</th>
<th>Threshold for Masking ( W \text{ m}^{-2} \text{ arcsec}^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>WISE W3</td>
<td>( 2.2 \times 10^{-16} )</td>
</tr>
<tr>
<td>32</td>
<td>WISE W2</td>
<td>( 8.0 \times 10^{-18} )</td>
</tr>
<tr>
<td>33</td>
<td>WISE W1</td>
<td>( 1.1 \times 10^{-17} )</td>
</tr>
<tr>
<td>36</td>
<td>FSQ [OIII]</td>
<td>( 4.0 \times 10^{-18} )</td>
</tr>
<tr>
<td>37</td>
<td>FSQ Hβ</td>
<td>( 2.3 \times 10^{-18} )</td>
</tr>
<tr>
<td>38</td>
<td>GALEX NUV</td>
<td>( 2.1 \times 10^{-17} )</td>
</tr>
</tbody>
</table>

Table 9.1: Data cube slices used in constructing the star mask, along with threshold values for inclusion in the mask.
Figure 9.1:

The star mask used for radial analysis, shown as black pixels against a square-root scale image of the FSQ Hα data cube slice.

A pixel which is to be excluded from radial profile calculations. Figure 9.1 shows the Hα slice with the mask applied. Pixels included in the mask are shown in black in the image, and are simply excluded from any calculations made using the mask.

9.2 Abel Inversion

With the point sources masked, the next step was to construct a radial profile of diffuse emission for each data cube slice. A Python script was built which would
parse each frame into a set of concentric rings centered on the frame center at 6h 31m 55s right ascension +4° 56′ 34″ declination. The nebula within a one degree radius of this point was divided into twelve concentric rings of 5 arcminutes width, and an average intensity in W m$^{-2}$ arcsec$^{-2}$ was found for all unmasked pixels within each ring. The result was a simple radial profile in intensity vs. radius for the nebula in each band. These radial profiles are shown in Figure[9.2]. Note that the horizontal scale for each of these plots shows angular radius from the nebula center, from 0 to 1 degrees. Adopting the mean cluster distance from Gaia DR1 as the distance to the nebula, 1182 pc[99], this would correspond to a physical radius from 0 to 21 pc. A more detailed view of the radial profile for selected slices is shown in Figure[9.3]. Each radial profile was then used as input for an Abel inversion corresponding to emission in that spectral band.

An Abel inversion is a technique widely used in the analysis of the spectra of laboratory plasmas to determine the three dimensional structure of a plasma from two-dimensional observations of its emission[57]. Specifically, an integral inversion procedure determines the emission coefficients of the plasma. If we suggest that the Rosette might be spherical centered about the geometric center of the nebula as noted, this technique may be applied to test sphericity for emission sources in each band. Note that an Abel inversion will also work for cases of a cylindrical plasma viewed from the side, though we do not predict that the Rosette would have such a geometry.

First, we take the emitting material to be optically thin to the emitted wavelength. This is certainly true for the radio and the long wavelength infrared bands, but is less certain for the mid-IR thermal dust emission. The optical bands clearly have significant foreground extinction, as well. We define an impact parameter, $y$, which is the distance of the closest approach of a given chord to the center of the sphere. Because the Rosette is projected in two-dimensions in our data, $I(y)$ is the observed flux as a function of the impact parameter, and can be expressed as follows.

$$I(y) = 2 \int_{0}^{\sqrt{r_0^2-y^2}} \epsilon(r) dx$$ (9.1)

Here, $\epsilon(r)$ is the emission as a function of radius in three dimensions, and $x$ is the variable along the optical path. The integral is done from $x = 0$, the point closest to the observer, to the outermost edge where the distance from the center is equal to $r_0$, the radius of the sphere itself. Any point beyond $r_0$ is taken to have zero emission. The factor of two accounts for the symmetry of the incoming and outgoing portions of the path[58].

Because the impact parameter $(y)$ is fixed, the radius is simply

$$r^2 = \sqrt{x^2 + y^2}$$ (9.2)

and consequently we can find $x$ through a simple rearrangement of terms. Differentiating $x^2 = r^2 - y^2$ in $x$ with constant $y$ returns $2x dx = 2r dr$ or, simplifying

$$dx = \frac{r dr}{x}$$ (9.3)
Figure 9.2:

Flux vs. observed radius from center for each data slice cube, organized by slice index in order of increasing frequency. The horizontal scale is angular distance from the nebula center, from 0 to 1 degrees.
If we substitute in \( x = \sqrt{r^2 - y^2} \) for \( x \) in this expression, we get

\[
dx = r\, dr/\sqrt{(y^2 - r^2)} \quad (9.4)
\]

With this, we can change the variable of integration in \( 9.1 \) from \( x \) to \( r \), with the resulting from

\[
I(y) = 2 \int_{y}^{r_0} \frac{\epsilon(r)r\, dr}{\sqrt{(y^2 - r^2)}} \quad (9.5)
\]

This is an expression for the intensity in terms of the impact parameter and emission as a function of radius, but since the measured quantity here is the intensity what is needed is an expression for the emission as a function of radius in terms of the measured \( I(y) \). To accomplish this, we utilize an Abel inversion to produce the expression

\[
\epsilon(r) = -\frac{1}{\pi} \int_{r}^{r_0} \frac{I'(y)\, dy}{\sqrt{(y^2 - r^2)}} \quad (9.6)
\]

Here, \( I'(y) \) is the derivative of \( I(y) \) \[57\]. A Python script was constructed to apply this transformation to each of the extracted radial profiles, and the resulting inverted Abel flux is plotted against radius for each slice in Figure 9.4. Again, a detailed view for selected slices is shown in Figure 9.5.

As can be seen in the figure, the vast majority of slices show a sharp dip below zero towards the center of the nebula, indicating a negative emitter density, which is unphysical. For the majority of these wave bands, then, the distribution cannot be uniformly spherical. This appears to be true for the neutral hydrogen and free-free emission in the radio (1-3), the dust and forbidden line emission throughout the mid to high frequency microwave and across the IR bands (9-33), as well as the optical emission from hydrogen, sulfur, and oxygen (34-37).
Figure 9.4:

Abel inverted flux vs. observed radius from center for each data slice cube, organized by slice index in order of increasing frequency. The horizontal scale is angular distance from the nebula center, from 0 to 1 degrees.
Abel inverted flux vs. radius from center for hydrogen emission at 21 cm and Hα (6563 Å).

Notable exceptions which according to this analysis could correspond to emission by a spherical distribution of emitters are the low frequency microwave (4-8) and the near ultraviolet (38). These may correspond to thermal emission by very large grain dust, in the case of the microwave bands, and scatter from said large dust grains in the case of the ultraviolet. If this is the case, it implies a more homogeneous distribution of this dust throughout the Rosette region than exists for the other material, which is consistent with the idea that large grain dust can survive in intense radiation fields where smaller grains are vaporized by photoablation. This model is further supported by the SED plot, which shows thermal continuum emission in these microwave bands corresponding to the coldest (30K) temperature curve, implying more distant dust grains possibly of greater size.

It should be noted that Abel inversion assumes an extinction-free radial profile, and the impact of extinction on these profiles is significant in some bands. We have already discussed at length the extinction in optical bands, though because the extinction across the visible portions of the nebula is essentially uniform around and across the central cavity (as shown in both the optical and radio derived extinction maps) extinction alone does not account for the negative density values predicted by Abel inversion in the optical bands. The negative central values in the Abel inversion for the 21 cm hydrogen line (slice 1) confirms that the source of this phenomenon must be the geometry of the gas itself, as extinction is not a factor in this band.

It is well-known that extinction from dust is even more pronounced in the ultraviolet regime, so the GALEX data (slice 38) is likely strongly impacted by both absorption and scattering of foreground dust. This would further account for the apparent sphericity of the Abel profile in this slice.

Beyond the optical and UV regimes, the impact of extinction is more limited. In general, continuum absorption is considered negligible for any wavelength greater
than 5 µm, though discrete absorption lines due to vibrational modes in the solid dust grains exist between 5 and 12 µm. The shortest wavelength WISE bands (slices 32 & 33, Figures [5.43 and 5.42] are still impacted by small amounts of continuum dust absorption. More significantly, the bandwidth of these two slices overlap several pronounced vibrational absorption bands, including the C-H present in a number of hydrocarbons around 3.3 µm and the C=O stretch around 4.6 µm. Since these WISE bands are also rich in emission from these same hydrocarbons, the interplay in these bands is likely too complex to be accurately modelled with a simple radial profile and Abel inversion [168].

The 12 µm slice may experience line absorption from a libration spectral line of H$_2$O, but this is the only likely source of extinction in that frame [168]. Beyond 12 µm in wavelength, slice bandwidths do not intersect known strong absorption features of this kind. The far IR, microwave, and radio bands (slices 1 - 27) may be taken to be effectively free of extinction due to dust [168].

9.3 Modeling

The Rosette Nebula appears to have circular symmetry in all the data cube slices. This is evident both from the data cube images and from the radial profiles presented previously. In particular, this apparent circular geometry is consistent both in the radio bands (as represented in Figure 5.11), which are largely free of attenuation due to interstellar dust, and the optical (see Figure 5.45), where the dust may be opaque. The apparent symmetry must result from a spatial distribution that seen from our location presents a nearly circular appearance. It could be a non-uniform sphere with an undetermined radial distribution, a torus seen face on, or something more cylindrical with its axis pointing approximately toward us. A non-spherical geometry which appears circularly symmetric would require the accidental orientation pointing an axis of symmetry toward us. If, for example, we consider the symmetry constraining the axis to within 10° to the line of sight, that would mean the axis would point within a solid angle $d\Omega$

$$\int d\Omega = \int_0^{\pi/18} \sin \theta \, d\theta \int_0^{2\pi} d\phi$$

$$\Omega = (1 - \cos(\pi/18)) \cdot 2\pi$$

$$\Omega = 0.308$$

out of 2π steradians (since it is bidirectional). The probability of a random orientation falling in that region would be ≈ 5%. Thus it is more likely by a factor of 20 that we are seeing a spherical object, and that the radial distribution of material in it is responsible for its appearance. Furthermore, a clue to the true 3-dimensional structure could come from extinction, which is itself a distance indicator if the material responsible for it is uniformly distributed.

Therefore as a first approximation to the Rosette we take a spherical model and test it against the observed flux distribution assuming uniform internal extinction.
However, the results of the previous Abel analysis made it clear that the Rosette could not be modeled with the standard Strömgren sphere, ionized hydrogen in a uniform spherical distribution about the ionization sources. The negative density evident in the Abel inverted profile of most of the data cube slices demands a non-uniformity in the distribution of emitting material throughout the sphere volume, specifically suggesting a dramatic decrease towards the center of the sphere. The idea of a central “bubble” is well supported in recent literature [16] [138], and would explain the sharp drop in diffuse emission towards the center of the object. Furthermore, the bright ring surrounding the central cavity in the H\(\alpha\) and H\(\beta\) slices would readily be accounted for by limb brightening due to this circular shell.

While earlier we performed an Abel inversion of the image data to directly yield a radial model, in this analysis we reverse the process and propose a non-uniform radial model which is fitted to the data. The advantage to this approach is that the fitting yields a best or most probable model, while an inversion may lead to singularities or to non-physical solutions. Ultimately the same spatial distribution of material, coupled with an excitation model, should yield fluxes which match those observed in different spectral passbands, and thus provide a completely consistent 3-dimensional model of the Rosette and its internal physics.

**The Simplest Structure**

To account for the central cavity, we need a model in which the inner regions have less material than the outer ones. That is, a uniform sphere will not reproduce the observations, but a sphere with the center removed, i.e. a shell with depth, could serve as the simplest basic model to compare to the observed data. A view of this model with its parameters is in Figure 9.6.

The parameters which describe this model are the radii of the bounding surfaces, \(r_{\text{inner}}\) and \(r_{\text{outer}}\), an absorption coefficient per unit length \(\kappa\), and an emission rate per unit length \(\epsilon\). The ray from the observer through the nebula has a path length \(p\) along a line that passes at impact parameter \(b\) from the center. Each pixel of an image recorded by a distant observer sums the light emitted along a ray. We assume no contribution to the signal from the central void, and also no contribution nor non-uniform absorption between the nebula and the observer. The image is therefore the integral over the path of the self-absorbed radiation.

**An Optical Model**

The detected light could be computed by integrating from the point of intersection of a ray with the outer sphere across the nebula to the point of intersection where it exits on the far side. If \(\zeta\) is the distance along the path, then the detected signal in the pixel through which the path passes is proportional to

\[
S = \int_0^p \epsilon \exp(-\kappa \zeta) \, d\zeta
\]

(9.10)

where the path begins at the entry point and proceeds to the exit point traveling a distance \(p\). The parameters \(\epsilon\) and \(\kappa\) are non-zero and positive constants inside the
Figure 9.6: The simplest model of the Rosette approximately consistent with its appearance in optical and radio frequency images. One optical path is only through the shell, and the other also passes through the central void. Both paths are attenuated by uniform absorption.
shell, and zero in the inner void. Along ray 1 in Figure 9.6

\[
S = (\epsilon \exp(-\kappa \zeta) /(-\kappa)) |_0^p
\]

\[
= \epsilon (1 - \exp(-\kappa p)) / \kappa
\]

(9.11)

(9.12)

In the limit of low absorption, the first few terms of the Taylor series for the exponential can be used and this becomes simply

\[
S = \epsilon (1 - (1 - \kappa p + (\kappa p)^2 + \cdots)) / \kappa
\]

\[
= \epsilon p (1 - p\kappa / 2 + \cdots)
\]

(9.13)

(9.14)

Thus when the absorption is very large it obscures the details of the inner structure, and the central hole is lost. The emission arises from the outer layers of the nebula over a path of the order of \( \kappa^{-1} \). When the absorption is small, the emission is proportional to the full path through the nebula diminished by the small absorption. In that case, the inner structure would be apparent. With increasing absorption the inner void appears to fill in, and the fall off of flux at the outer edge is diminished because the observed emission is all from the outermost \( \kappa^{-1} \) in the structure.

Consider the possible paths illustrated in Figure 9.6. The pathlength \( p \) for Ray 1 is given by

\[
p = 2 \sqrt{r_{\text{outer}}^2 - b^2}
\]

(9.15)

in terms of the impact parameter \( b \) allowing for the spherical symmetry. The actual computation is simplified if the sphere is centered on \((0, 0, 0)\) in the spatial coordinate system, and if we view the sphere along the \( z \) axis. In that instance, it is

\[
b = \sqrt{\xi^2 + \eta^2}
\]

(9.16)

where \((\xi, \eta)\) is the location of the pixel projected onto the 2-dimensional scene.

Similarly, the effective pathlength for Ray 2 is

\[
p = 2 (\sqrt{r_{\text{outer}}^2 - b^2} - \sqrt{r_{\text{inner}}^2 - b^2})
\]

(9.17)

since there is no contribution from inside \( r_{\text{inner}} \). In computing the emergent flux, when \( b > r_{\text{outer}} \) there is no emission, when \( b < r_{\text{outer}} \) and \( b > r_{\text{inner}} \) we follow Equation 9.15 and when \( b < r_{\text{inner}} \) we follow Equation 9.17.

**Python Code**

A Python program to generate a FITS image file matching the image slices of the multi-spectral database was written to implement this model. The portion that computes the signal is a loop over two dimensions of the image, integrating along the optical path for each pixel. The model is built using parsecs for the internal distance scale such that the absorption coefficient \( \kappa \) is in units of parsec\(^{-1} \). The pixel scale is set to match the field of view of the database images.
surfaceimage = zerosimage

# Path length is p
# Use exact solution for absorption, absk > 1.e-6 per parsec

for i in range(xsize):
    for j in range(ysize):
        # Impact parameter
        b = ma.sqrt((x[j,i])**2 + (y[j,i])**2)
        if b > router:
            # Sight line outside the outer radius
            surfaceimage[j,i] = 0.
        elif b >= rinner:
            # Sight line inside the outer radius and outside the inner radius
            p = 2.*ma.sqrt(router**2 - b**2)
            if absk < 1.e-6:
                surfaceimage[j,i] = emissionrate*p
            else:
                surfaceimage[j,i] = emissionrate*(1. - ma.exp(-absk*p))/absk
        else:
            # Sight line inside the inner radius
            # Assumes nothing inside the inner radius
            pouter = 2.*ma.sqrt(router**2 - b**2)
            pinner = 2.*ma.sqrt(rinner**2 - b**2)
            p = pouter - pinner
            if absk < 1.e-6:
                surfaceimage[j,i] = emissionrate*p
            else:
                surfaceimage[j,i] = emissionrate*(1. - ma.exp(-absk*p))/absk

The image is stored as a numpy array `surfaceimage` and indexed by `[column,row]` which also provide values of the spatial positions `x` and `y` through two helper arrays. At each position the impact parameter `b` is computed and evaluated for the sight line. The total emission from the surface as seen at that pixel is evaluated based on the intersection of the line with the model’s structure. Within that structure, the assumptions are made that

- the emitting gas is evenly distributed in a spherical shell,
- there is uniform self-absorption within the shell,
- the interior is empty,
- the excitation is uniform throughout the shell, and
- there is no non-uniform external absorption.
Figure 9.7: Three model images from the Python code for different values of the absorption coefficient: 0.025, 0.050, and 0.10 pc$^{-1}$.

In the code listing, the absorption coefficient is $\text{absk} = \kappa$ and the emission coefficient is $\text{emissionrate} = \epsilon$. Not shown here, the result is exported to a FITS image file in the same format used for the real data.

Figure 9.7 illustrates the result of running this code assuming an inner radius of 4.75 pc and an outer radius of 12.44 pc based on matching the size to the datacube images and assuming a distance to the center of 1200 pc. The radii would scale inversely with distance. For different absorption coefficients, the expected effects of increasing absorption on the appearance of the nebula show here. The center fills in as the absorption increases, the “limb darkening” is more obvious at lower absorption. The highlight of the nebula close to the inner boundary in the models is also suggestive of the appearance of the nebula in H$\alpha$. This is the region where the path is longest, and the highlight effect diminishes in the models especially for absorption greater than 0.1 pc$^{-1}$. There is also a pronounced similarity in appearance to the 21 cm hydrogen emission.

**Javascript and GLSL Visualization**

An interactive 3D model incorporating the concepts of the Python code was then constructed in Javascript. The 3D visualization itself is built using the Three.js library of routines [156], and displayed using the WebGL API to javascript which facilitates 3D web display. The complete program is included in an appendix, but the portion of the code which models nebula glow bears special attention. One strength of this implementation is that the resulting program allows viewing the 3D bounding surfaces, and placing them in a spatial context to assist visualizing how they determine the observable features of the nebula. An example of the screen showing a wireframe view and the menu system is in Figure 9.8.

This visualization allows control of the glow parameters, external lighting, choice of structural components, and the shading via dropdown menu. In this example the wireframe shows the lines and vertices defining the surfaces. The shader, which
Figure 9.8: A wire frame model of the Rosette shell structure shown in the Javascript version of the code running within the Google Chrome browser. implements a realistic display from this information, takes each vertex one by one and computes how it will appear in the screen image. This mirrors the logic of the Python program which takes each pixel of the image and computes the contributions to it from the space behind it. A rendered visualization is shown in 9.9.

At present (November 2016) Three.js is a surface rendering library and its capabilities for transparent volume visualization are limited to managing the Fresnel equations for refraction and reflection at boundaries, but not including physically accurate light scattering or light sourcing within the volume. There has been considerable effort in this direction that takes advantage of the OpenGL Shading Language (GLSL) shader code that runs on the GPU of the host computer, and calculates the intensity at each pixel vertex by vertex for the scene geometry. With it, light scattering and absorption in Earth’s atmosphere have been treated with physics-based models, and the methods developed for that can be extended to this problem. [108]
As a step in that direction, we take this approach here and use the shader language to add effective representation of the light from within the volume bounded by the surface.

Each vertex of the bounding surface is treated one at a time, with no awareness of the rest of the scene. For a spherical geometry, the methods used in the Python code are sufficient. The vertex shader, a central component of the process, was adapted from an open source program Shader-Glow.html by Stemkoski [152].

A final representation of the three dimensional model is shown in Figure 9.10. In this example, the nebula radius is taken to be 12.44 pc, and an absorption coefficient of 0.75 (corresponding to a physical model scale of 0.060 pc$^{-1}$) is used. The result bears a strong resemblance to the data cube slices corresponding to both optical and radio hydrogen emission.

A background sky based on the Hipparcos catalog is included with the model [14].
Figure 9.10: A physics-based model of the Rosette emission shown in the Javascript version of the code running within the Google Chrome browser. The scaled absorption coefficient 0.75 units for the model corresponds to 0.06 pc\(^{-1}\).

This background is not scaled for distance, and upon rotation the star background moves as if all points were very distant from the nebula. This is not the case, so the star field serves only to create a sense of transparency to the nebula. The appearance of the emission in this rendering is identical to that in the Python version since they are based on the same underlying assumptions. We have added placeholders to the program to allow including other features such as the stars that are exciting the emission, localized dust, and foreground effects as they become better defined.

### 9.4 Density Estimate

This model provides a foundation to constrain the hydrogen density within the nebula. In our model the Rosette is essentially a modified Strömgren Sphere, where the volume
loss due to the central cavity must be accounted for \[96\]. Using Gaia data release 1, the mean distance to the ionizing cluster stars would be 1182 pc \[99\]. Geometric comparison to the angular measurements of the nebula estimates an inner cavity radius of 4.75 and an outer radius of 12.44 pc, as seen in our model. The volume of the emitting shell (inner sphere volume subtracted from outer sphere volume) would then be \(7.6 \times 10^3\) pc\(^3\). This is a volume of gas equivalent to a standard Strömgren Sphere of radius 12.2 pc. In the simplest approximation the ionized volume, which we have just determined, the strength of the ionizing source or sources, defined by the cluster stars, and the density of the hydrogen.

As a possible lower bound, consider the approximation that the O5V star HD46150 is the primary ionizing star of the nebula. Referencing table 2.3 on page 27 of Astrophysics of Gaseous Nebulae and Active Galactic Nucleii by Osterbrock and Ferland, we find that an O5V star with a surface temperature of 46,100 K produces \(10^{49.53}\) ionizing photons sufficient to create a Strömgren Sphere of radius 94 pc with a density of 1 cm\(^{-3}\) \[44\]. Within the sphere, the product of \(n^2\) and \(r^3\) would be constant, so for a sphere with the observed effective radius of 12.2 pc this implies a corresponding density of 21.4 cm\(^{-3}\).

At the opposite extreme, we consider the case where all O stars present in the cluster are fully contributing to the ionization of the nebula. Summing the contributions from the O4, O5, O8, O8.5, and two O9 cluster stars as summarized in that same table, we find a total of \(10^{50}\) ionizing photons/s being produced. This is equivalent to the ionizing photon output of an O3 III star, corresponding to a Strömgren radius of 134 pc \[44\]. Using the same constant relationship as before, we calculate a corresponding density of 36.4 cm\(^{-3}\) at this upper limit.

Future modeling will attempt to account for off center ionizing sources, variabilities in density, and interference from dust. Once Gaia data release 2 is available, defining the precise geometry of the cluster, it will be possible to conduct this analysis in greater detail.
Chapter 10 Conclusions and Future Work

10.1 Conclusions

We have collected wide field, deep exposures of the entire Rosette nebula, the North America Nebula, and the Orion Nebula across four narrow band optical filters (Hα, Hβ, [OIII], and [SII]). Wide slit spectra were also collected for all three objects, and these data were absolutely calibrated by reference to an absolute Vega flux measurement after correction for instrumental effects. The wide field data has been reduced, co-added, and combined into master frames. These masters have been corrected for reddening due to air mass and other atmospheric extinction effects and then flux-calibrated through comparison to the WISPI spectra, with independent validation of the Hα calibration by reference to Scherb’s absolute flux measurement of NGC 7000 [139] and Celnik’s absolute flux measurement of the Rosette nebula [24].

The Rosette nebula data was then resampled to a 2° square field with 1 arcsecond per pixel resolution and the flux rescaled to units of W m⁻² arcsec⁻². Archival data from the Effelsberg 100 m radio telescope, along with space-based observations from WMAP, Planck, Akari, IRAS, MSX, WISE, and GALEX, were then brought to the same spatial scale and flux units using SWarp for spatial scaling and a collection of custom Python scripts for energy rescaling. The result is a spatially consistent multispectral data cube of 38 individual slices on a uniform energy flux scale spanning the electromagnetic spectrum from the radio at 21 cm to the ultraviolet at 227 nm.

From ratios of data cube slices in the optical and radio bands, we have generated spatial maps of V-band foreground extinction which confirm color-color extinction estimates for NGC 2244 while providing new, high resolution extinction estimates for the surrounding gas. These maps also serve to allow extinction corrections of other data products. Using the [OIII]/[SII] ratio, we have also created a map of the spatial dependence of the ionization parameter across the nebula, highlighting variations in gas density and the radiation field throughout the object.

While pursuing a line-of-sight absorption spectrum of an anomalous elephant trunk structure in the center of the Rosette using the University College London Echelle Spectrograph on the Anglo-Australian 3.9 m telescope, we have discovered a young solar twin in the local bubble and extracted many of its physical parameters. This same study also provided estimates of radial velocity and independent line ratio measurements for the background nebula gas.

Finally, we have generated radial profiles and Abel inversions for all data cube slices and used these to inform a simple three dimensional model for the Rosette nebula. Based on this analysis, we propose that the nebula is structured as a thick shell of hydrogen surrounding an evacuated cavity, which contains the ionizing stars which drive the nebula. This morphological model is presented in two dimensions using custom Python code, and the resulting visualizations bear a striking resemblance to the unextinguished 21 cm hydrogen data which traces the structure of the ionized gas. A three dimensional model built in javascript and GLSL using the Three.js library...
has also been presented, with significant flexibility for expansion in the future. An estimate of gas density has been derived from the modeled geometry of the object.

10.2 Future Work

In the course of completing this work, a huge variety of possibilities for further analysis have presented themselves.

The second data release for the Gaia mission is currently planned for April 2018 [50]. This data release will include high precision parallax distance measurements for many stars in NGC 2244, including all of the O-type ionizing sources. The result will be a much more accurate distance measurement for the cluster, as well as a significant clarification of the geometry of the cluster itself. The relation of the gas to the ionizing sources will therefore be considerably clearer, and significant revisions can be made to the model in light of this new information. More precise cluster geometry may also provide targets for follow-up analysis of the anomalous “rogue” trunk feature.

CHANDRA data is only available for the central cluster and a small region to the south east, so was not incorporated into the data cube. However, further processing and integration of this data would inform future modelling. CHANDRA data requires special handling via a proprietary processing engine, so future work will involve reducing and integrating available data into a “cut out” of the data cube which will show the previously discussed 10 MK diffuse emission within the central cavity as well as x-ray sources within the selected region.

A major focus of future work will likely be enhancing and expanding the model. One immediate priority is moving to a model capable of asymmetric density variations. This would allow us to directly account for the lower density, matter-bounded north east rim of the nebula where it intersects the supernova loop. A density and consequent emission drop here will emulate the evident “dent” in the corresponding region of the radio emission maps. To further expand on the modelling, CLOUDY3D will be used to account for non-hydrogen chemical abundances, dust, and other factors beyond the scope of the current model.

The SED analysis presented here is a first pass, future SED analysis will seek more sophisticated thermal curve fitting and attempt to differentiate more clearly between dust regions in an effort to derive a more complete understanding of the three dimensional distribution of warm dust in the Rosette region. Toward this end, integration of Spitzer and Herschel data, which is only available for portions of the nebula, will be helpful. Further investigation of methods for determining grain size and composition will also be a priority. Incorporation of additional infrared sources and spectroscopy may also inform further investigation of the anomalous “rogue trunk” feature.

Given the known richness of diffuse interstellar bands in the Rosette region, we would like to pursue an investigation of line of sight absorption by interstellar lines using stars in the cluster. This was part of the motivation for the existing UCLES study, and that analysis provided valuable experience which could be put toward this broader task.
Follow-up observations of the Rosette targeted towards the isolation of additional physical parameters would be hugely beneficial to continued analysis of this object. Spectroscopy with higher spectral resolution would allow a comparison of the relative strength of the [SII] doublet lines, providing an estimate of electron density in targeted regions of the nebula. In combination with existing derived parameters such as foreground extinction, the thickness of the nebula could be estimated thereby significantly enhancing the model [44].

Similarly, higher sensitivity spectroscopy would allow a comparison of the [OIII] lines, from which the electron temperature can be determined. If a filter for isolating the 4363 Å line could be acquired and a spatial map constructed, it could be combined with the existing 5007 Å map to create a spatial map of electron temperature [44]. A better understanding of electron temperature distribution throughout the nebula would inform further modelling and also provide more precise model radio emission for the radio-derived extinction map. Additional filters would allow spatial mapping of N and He lines, charting the abundances of these elements and further informing the model.

Finally, there is ample opportunity for applications of the techniques developed throughout this project to other emission nebulae. A broad survey of similar targets would yield further insight into the physics and morphology of these important objects.


206
Appendix A: Commonly Used Acronyms

AAT - Anglo-Australian Telescope
GALEX - Galaxy Evolution Explorer
HFI - Planck’s High Frequency Instrument
HPBW - Half Power Beam Width
IRAS - Infrared Astronomical Satellite
IRSA - Infrared Science Archive
LFI - Planck’s Low Frequency Instrument
LTE - local thermodynamic equilibrium
JAXA - Japanese Aerospace Exploration Agency
JPL - Jet Propulsion Laboratory
LAMBDA - Legacy Archive for Microwave Background Data Analysis
MAST - Mikulski Archive for Space Telescopes
MSX - Midcourse Space Experiment
NASA - National Aeronautics and Space Administration
PAH - polycyclic aromatic hydrocarbons
PDR - photodissociation region
PSF - point spread function
SED - spectral energy distribution
SNR - supernova remnant
UCLES - University of London Echelle Spectrograph
WCS - world coordinate system
WISE - Widefield Infrared Survey Explorer
WISPI - Widefield Spectral Imager
WMAP - Wilkinson Microwave Anisotropy Probe
YSO - young stellar object
ZAMS - zero age main sequence
Appendix B: Model Code

<!DOCTYPE html>
<html lang="en">
<head>
  <title>Rosette Nebula Geometry</title>
  <meta charset="utf-8">
  <meta name="viewport" content="width=device-width, 
user-scalable=no, 
minimum-scale=1.0, 
maximum-scale=1.0">
  <style>
    body {
      color: #fff;
      font-family: Monospace;
      font-size: 13px;
      text-align: center;
      font-weight: bold;

      background-color: #000;
      margin: 0px;
      overflow: hidden;
    }

    #info {
      position: absolute;
      padding: 10px;
      width: 100%;
      text-align: center;
      color: #fff;
    }

    a { color: blue; }
  </style>
</head>
<body>
<div id="info">
  <a href="http://www.astro.louisville.edu" target="_blank">University of Louisville Physics & Astronomy</a>
</div>
</body>
</html>
Jeremy Huber – Rosette Nebula

<!— ThreeDotJS —>

<script src="js/three.min.js"></script>

<!— Shaders adapted from http://stemkoski.github.io/Three.js/Shader-Glow.html —>

<script id="starvertexShader" type="x-shader/x-vertex">
    varying float intensity;
    void main()
    {
        intensity = 1.;
        // Pass the 2D position for this vertex to the shader
        gl_Position = projectionMatrix * modelViewMatrix *
                     vec4( position, 1.0 );
    }
</script>

<script id="starfragmentShader" type="x-shader/x-vertex">
    uniform vec3 starglowColor;
    varying float intensity;
    void main()
    {
        vec3 glow = starglowColor * intensity;
        gl_FragColor = vec4( glow, 1.0 );
    }
</script>

<script id="clustervertexShader"
    type="x-shader/x-vertex">
    void main()
    {
        // Pass the 2D position for this vertex to the shader
        gl_Position = projectionMatrix * modelViewMatrix *
                     vec4( position, 1.0 );
    }
</script>
<script id="clusterfragmentShader" type="x-shader/x-vertex">
uniform vec3 clusterGlowColor;

void main()
{
  vec3 glow = clusterGlowColor * 1.0;
  gl_FragColor = vec4(glow, 1.0);
}
</script>

<script id="vertexShader" type="x-shader/x-vertex">
uniform vec3 viewVector;
uniform float erate;
uniform float arate;
varying float intensity;
varying float inner;
varying float outer;
varying float rpix;
varying float b;
varying float path;
varying float syntheta;
varying float costheta;
varying float emissionrate;
varying float absk;

void main()
{

  // vec3 vNormal = normalize( normalMatrix * normal );
  vec3 vNormal = normalize( normalMatrix * position );
  vec3 vNormal = normalize( normalMatrix * viewVector );
  costheta = dot(vNormal, vNormal);
  syntheta = sqrt(1. - costheta * costheta);

  // Note we do not test for the back side for which
  // costheta would be negative
  // Assuming only the front side is being processed
  // by the shader

  // Normalized emission rate per parsec within the
  // nebula
  emissionrate = erate / 12.44;

</script>
Absorption coefficient per parsec within the nebula
\[ \text{absk} = \text{arate} / 12.44; \]

Inner and outer radii of the model are hard-coded here
These are GL units scaled at 1 unit/pc
Estimated from H alpha and ds9 would be 3.3 pc
\[ \text{rinner} = 4.75; \]
\[ \text{router} = 12.44; \]
\[ \text{b} = \text{router} \times \text{sintheta}; \]

Mark the inner surface if present and ignore
\[ \text{rpix} = \sqrt{\text{position}.x \times \text{position}.x + \text{position}.y \times \text{position}.y + \text{position}.z \times \text{position}.z}; \]
if \( \text{rpix} < 1.01 \times \text{rinner} \&\& \text{rpix} > 0.9 \times \text{rinner} \)
{
    // Mark the inner boundary by selecting only the inner surface vertices
    // This will not show if the inner region is deselected in the GUI
    \[ \text{intensity} = \text{pow}(0.4 - \text{dot}(<vNormal>, <vNormel>), 1.0); \]
}
else
{
    // Compute a physical model for the shell emission
    if \( \text{b} > \text{rinner} \)
    {
        \[ \text{path} = 2. \times \sqrt{\text{router} \times \text{router} - \text{b} \times \text{b}}; \]
    }
    else
    {
        \[ \text{path} = 2. \times \sqrt{\text{router} \times \text{router} - \text{b} \times \text{b}} - 2. \times \sqrt{\text{rinner} \times \text{rinner} - \text{b} \times \text{b}}; \]
    }
    if \( \text{absk} \times \text{path} > 1.e-3 \)
    {
        // Use exact solution
    }
intensity = emissionrate*(1. - exp(-absk*path))/absk;
}
else
{
  // Use leading 3 terms of Taylor series for exponential
  intensity = emissionrate*path*(1. - absk*path*0.5);
}

// Pass the 2D position for this vertex to the shader
gl.Position = projectionMatrix * modelViewMatrix * vec4(position, 1.0);

<script id="fragmentShader" type="x-shader/x-vertex">
uniform vec3 glowColor;
varying float intensity;
void main()
{
  vec3 glow = glowColor * intensity;
  gl_FragColor = vec4(glow, 1.0);
}</script>

<!— Navigation control —>
if ( ! Detector.webgl ) Detector.addGetWebGLMessage();

var camera, scene, sceneCube, renderer;
var cameraControls;
var effectController;
var ambientLight, light;

var init = 0; // force initialization
var binner;
var bouter;
var bgaia;
var bcluster;
var bdust;
var bstars;
var shading;
var wireMaterial, flatMaterial, gouraudMaterial,
    phongMaterial, texturedMaterial, glowMaterial,
    starMaterial;

var innernebula;
var outernebula;
var stars;
var gaia;
var cluster;

// allocate these just once
var diffuseColor = new THREE.Color();
var specularColor = new THREE.Color();

init();
render();

// Set up the environment
function init() {

    container = document.createElement( 'div' );
document.body.appendChild( container );

    var canvasWidth = window.innerWidth;
    var canvasHeight = window.innerHeight;

    // CAMERA
camera = new THREE.PerspectiveCamera( 45, window.innerWidth / window.innerHeight, 1, 80000 );
// Distance to Rosette center should be 1182 pc
//camera.position.set( -600, 550, 1300 );
camera.position.set( 0., 0., 1182. );

// LIGHTS
ambientLight = new THREE.AmbientLight( 0x333333 );
// 0.2
light = new THREE.DirectionalLight( 0xFFFFFF, 1.0 );
// direction is set in GUI

// RENDERER
renderer = new THREE.WebGLRenderer( { antialias: true } );

// Set the default background without stars
// Use a deep blue with a little red to evoke night sky 0x200040
renderer.setClearColor( 0x000000 );
renderer.setSize( window.innerWidth, window.innerHeight );
renderer.gammaInput = true;
renderer.gammaOutput = true;
container.appendChild( renderer.domElement );

// EVENTS
window.addEventListener( 'resize', onWindowResize, false );

// CONTROLS
cameraControls = new THREE.OrbitControls( camera, renderer.domElement );
cameraControls.target.set( 0, 0, 0 );
cameraControls.addEventListener( 'change', render );

// TEXTURE MAP
var textureMap = new THREE.TextureLoader().load( 'textures/UV_Grid_Sm.jpg' );
textureMap.wrapS = textureMap.wrapT = THREE.RepeatWrapping;
textureMap.anisotropy = 16;
// MATERIALS
var materialColor = new THREE.Color();
materialColor.setRGB(1.0, 1.0, 1.0);

wireMaterial = new THREE.MeshBasicMaterial({ color: 0xFFFFFF, wireframe: true });

flatMaterial = new THREE.MeshPhongMaterial({ color: materialColor, specular: 0x0, shading: THREE.FlatShading, side: THREE.DoubleSide, opacity: 0.5, transparent: true });

gouraudMaterial = new THREE.MeshLambertMaterial({
color: materialColor, side: THREE.DoubleSide,
opacity: 0.5, transparent: true }
);

phongMaterial = new THREE.MeshPhongMaterial(
{
color: materialColor, shading: THREE.SmoothShading, side: THREE.DoubleSide,
opacity: 0.5, transparent: true }
);

texturedMaterial = new THREE.MeshPhongMaterial(
{
color: materialColor, map: textureMap, shading: THREE.SmoothShading, side: THREE.DoubleSide,
opacity: 0.5, transparent: true }
);

starglowMaterial = new THREE.ShaderMaterial(
{
uniforms:
{
starglowColor: { type: "c", value: new THREE.Color(0xa0a0ff) }
},
vertexShader: document.getElementById('starvertexShader').textContent,
fragmentShader: document.getElementById('starfragmentShader').textContent,
side: THREE.FrontSide,
blending: THREE.AdditiveBlending,
transparent: false
});
// Shader for cluster
// Does not work if cluster is offset and transparent

clusterGlowMaterial = new THREE.ShaderMaterial(
{
    uniforms:
    {
        clusterGlowColor: { type: "c", value: new THREE.Color(0x4000ff) },
    },
    vertexShader: document.getElementById('clustervertexShader').textContent,
    fragmentShader: document.getElementById('clusterfragmentShader').textContent,
    side: THREE.FrontSide,
    blending: THREE.AdditiveBlending,
    transparent: false
} );

glowMaterial = new THREE.ShaderMaterial(
{
    uniforms:
    {
        "erate": { type: "f", value: 1.0 },
        "arate": { type: "f", value: 0.75 },
        glowColor: { type: "c", value: new THREE.Color(0xff0080) },
        viewVector: { type: "v3", value: camera.position }
    },
    vertexShader: document.getElementById('vertexShader').textContent,
    fragmentShader: document.getElementById('fragmentShader').textContent,
    side: THREE.FrontSide,
    blending: THREE.AdditiveBlending,
    transparent: true
} );

// scene itself
scene = new THREE.Scene();

scene.add( ambientLight );
scene.add(light);

stars = createStars(2000, 64);

// Rotate the stars to put us on a line of sight to the Rosette in the sky
stars.rotation.y = (11.5/24.)*2.*Math.PI;
stars.rotation.x = (-5.01/360.)*2.*Math.PI;

// scene.add(stars);

gaia = createGaia();
// scene.add(gaia);

cluster = createCluster();
// scene.add(cluster);

// GUI
setupGui();

}

// EVENT HANDLERS

// WINDOW
function onWindowResize() {

    var canvasWidth = window.innerWidth;
    var canvasHeight = window.innerHeight;

    renderer.setSize(canvasWidth, canvasHeight);

    camera.aspect = canvasWidth / canvasHeight;
camera.updateProjectionMatrix();

    render();
}

// DATA INPUT
function setupGui() {

    effectController = {

    }
shininess: 40.0,
ka: 0.17,
kd: 0.51,
ks: 0.2,
opacity: 0.5,
metallic: true,

hue: 0.121,
saturation: 0.50,
lightness: 0.50,

erate: 1.0,
arat: 0.75,
ghue: 0.5,
gsaturation: 0.5,
glightness: 0.5,

lhue: 0.04,
lsaturation: 0.50, // non-zero so that fractions will be shown
llightness: 0.50,

// initialize these with positive numbers
// otherwise sliders do not show decimal
places
lx: 0.32,
ly: 0.39,
lz: 0.7,
inner: true,
outer: true,
gaia: false,
cluster: false,
dust: false,
stars: false,
newShading: "glowing"
};

var h;

var gui = new dat.GUI();

// material (attributes)

h = gui.addFolder("Material_control");
h.add( effectController, "shininess", 1.0, 400.0, 1.0 ).name( "shininess" ).onChange( render );
h.add( effectController, "kd", 0.0, 1.0, 0.025 ).name( "diffuse_strength" ).onChange( render );
h.add( effectController, "ks", 0.0, 1.0, 0.025 ).name( "specular_strength" ).onChange( render );
h.add( effectController, "opacity", 0.0, 1.0, 0.025 ).name( "opacity" ).onChange( render );
h.add( effectController, "metallic" ).onChange( render );

// material (color)

h = gui.addFolder( "Material_color" );
h.add( effectController, "hue", 0.0, 1.0, 0.025 ).name( "hue" ).onChange( render );
h.add( effectController, "saturation", 0.0, 1.0, 0.025 ).name( "saturation" ).onChange( render );
h.add( effectController, "lightness", 0.0, 1.0, 0.025 ).name( "lightness" ).onChange( render );

// glow (color)

h = gui.addFolder( "Glow" );
h.add( effectController, "erate", 0.0, 3.0, 1.0 ).name( "emission" ).onChange( render );
h.add( effectController, "arate", 0.0, 3.0, 0.75 ).name( "absorption" ).onChange( render );
h.add( effectController, "ghue", 0.0, 1.0, 0.5 ).name( "hue" ).onChange( render );
h.add( effectController, "gsaturation", 0.0, 1.0, 0.5 ).name( "saturation" ).onChange( render );
h.add( effectController, "gLighntness", 0.0, 1.0, 0.5 ).name( "lightness" ).onChange( render );

// light (color and intensity)

h = gui.addFolder( "Lighting_color" );
h.add( effectController, "lhue", 0.0, 1.0, 0.025 ).name( "hue" ).onChange( render );
h.add( effectController, "lsaturation", 0.0, 1.0, 0.025 ).name( "saturation" ).onChange( render );
h.add( effectController, "llightness", 0.0, 1.0, 0.025 ).name("llightness").onChange(render);

h.add( effectController, "ka", 0.0, 1.0, 0.025 ).name("ambient").onChange(render);

// light (direction)

h = gui.addFolder("Lighting direction");

h.add( effectController, "lx", -1.0, 1.0, 0.025 ).name("x").onChange(render);

h.add( effectController, "ly", -1.0, 1.0, 0.025 ).name("y").onChange(render);

h.add( effectController, "lz", -1.0, 1.0, 0.025 ).name("z").onChange(render);

h = gui.addFolder("Model control");

h.add( effectController, "inner" ).name("Display inner").onChange(render);

h.add( effectController, "outer" ).name("Display outer").onChange(render);

h.add( effectController, "gaia" ).name("Display GAIA").onChange(render);

h.add( effectController, "cluster" ).name("Display NGC 2244").onChange(render);

h.add( effectController, "dust" ).name("Display dust").onChange(render);

h.add( effectController, "stars" ).name("Display field stars").onChange(render);

// shading

h = gui.add( effectController, "newShading", ["wireframe", "flat", "smooth", "glossy", "textured", "glowing"] ).name("Shading").onChange(render);

}

// REAL SKY

function createStars(radius, segments) {
  return new THREE.Mesh(new THREE.SphereGeometry(radius, segments, segments),

new THREE.MeshBasicMaterial({
    map: new THREE.TextureLoader().load('textures/realsky/bourne_4096x2048.png'),
    side: THREE.BackSide
});

//-- GAIA STARS

// HD 46149 (O8V/O8.5V)
// 2015 ICRS
// 97.96887635547564
// 5.033106538115286
// 0.81756580423408
// 1.223 kpc

// HD 46202 (O9.5V)
// 2015 ICRS
// 98.04361985142576
// 4.966600511939007
// 0.7613938885450916
// 1.313 kpc

// HD 46150 (O5V)
// 2015 ICRS
// 97.981326796313
// 4.9428593278988195
// 1.0574697442431706
// 0.946 kpc

// HD 46056 (O8V)
// 2015 ICRS
// 97.83691243517836
// 4.8344011125399575
// 0.744103094509757
// 1.3439 kpc

// HD 46223 (O4V)
// Distance in pc from center of the Rosette
// Z is + toward the camera
// Y is + up
// X is + right

var star1x = 0.107684;
var star1y = 0.626549;
var star1z = -41.509801;

var star2x = -0.985798;
var star2y = -0.307267;
var star2z = -131.747;

var star3x = -0.048847;
var star3y = -0.473135;
var star3z = 235.979800;

var star4x = 2.108136;
var star4y = -2.307777;
var star4z = -162.266467;
var star5x = -0.797375;
var star5y = -2.106526;
var star5z = 36.283828;
var star6x = -6.094599;
var star6y = -5.798562;
var star6z = 63.007436;

var starGeometry = new THREE.SphereGeometry( 0.4, 30, 30);

starsphere1 = new THREE.Mesh( starGeometry, shading = starglowMaterial );
starsphere1.position.set( star1x, star1y, star1z );
starcluster.add( starsphere1 );
starsphere2 = new THREE.Mesh( starGeometry, shading = starglowMaterial );
starsphere2.position.set( star2x, star2y, star2z );
starcluster.add( starsphere2 );

starsphere3 = new THREE.Mesh( starGeometry, shading = starglowMaterial );
starsphere3.position.set( star3x, star3y, star3z );
starcluster.add( starsphere3 );
starsphere4 = new THREE.Mesh( starGeometry, shading = starglowMaterial );
starsphere4.position.set( star4x, star4y, star4z );
starcluster.add( starsphere4 );

starsphere5 = new THREE.Mesh( starGeometry, shading = starglowMaterial );
starsphere5.position.set( star5x, star5y, star5z );
starcluster.add( starsphere5 );
starsphere6 = new THREE.Mesh( starGeometry, shading = starglowMaterial );
starsphere6.position.set( star6x, star6y, star6z );
starcluster.add( starsphere6 );

return starcluster;
function createCluster() {
    var starsphere3;
    var starcluster = new THREE.Object3D();
    var starGeometry = new THREE.SphereGeometry(4.53, 30, 30);

    // Distance in pc from center of the Rosette
    // Z is + toward the camera
    // Y is + up
    // X is + right

    // Using coordinates for HD 46150 at cluster z

    var star3x = -0.048847;
    var star3y = -0.473135;
    var star3z = 0.;

    // 24 arcmin is a catalog diameter for the cluster
    // At 1300 pc this would be 4.53 pc radius
    // Scaling is 1 pc per screen unit

    // var starGeometry = new THREE.SphereGeometry(4.53, 30, 30);

    starsphere3 = new THREE.Mesh(starGeometry, shading = clusterglowMaterial);
    starsphere3.position.set(star3x, star3y, star3z);
    starcluster.add(starsphere3);

    return starcluster;
}

// DO THE WORK

function render() {

    // If the model has changed we need to render it again
// We also do a render if it has not been rendered before

if ( initLine !== 1 ||
    effectController.inner !== binner ||
    effectController.outer !== bouter ||
    effectController.gaia !== bgai ||
    effectController.cluster !== bcluster ||
    effectController.dust !== bdust ||
    effectController.stars !== bstars ||
    effectController.newShading !== shading ) {

    initLine = 1;
    binner = effectController.inner;
    bouter = effectController.outer;
    bgai = effectController.gaia;
    bcluster = effectController.cluster;
    bdust = effectController.dust;
    bstars = effectController.stars;
    shading = effectController.newShading;

    createNewNebula();
}

// We set the illumination and material properties from current settings

flatMaterial.opacity = effectController.opacity;
gouraudMaterial.opacity = effectController.opacity;
phongMaterial.opacity = effectController.opacity;
texturedMaterial.opacity = effectController.opacity;

phongMaterial.shininess = effectController.shininess;
texturedMaterial.shininess =
    effectController.shininess;

diffuseColor.setHSL( effectController.hue,
    effectController.saturation,
    effectController.lightness );
if ( effectController.metallic ) {

    // make colors match to give a more metallic look
    specularColor.copy( diffuseColor );
}
else
{

    // more of a plastic look
    specularColor.setRGB(1, 1, 1);
}

diffuseColor.multiplyScalar(effectController.kd);
flatMaterial.color.copy(diffuseColor);
gouraudMaterial.color.copy(diffuseColor);
phongMaterial.color.copy(diffuseColor);
texturedMaterial.color.copy(diffuseColor);

specularColor.multiplyScalar(effectController.ks);
phongMaterial.specular.copy(specularColor);
texturedMaterial.specular.copy(specularColor);

// Nebular glow
glowMaterial.uniforms["erate"][value] =
effectController.erate;
glowMaterial.uniforms["arate"][value] =
effectController.arate;
glowMaterial.uniforms["glowColor"][value].setHSL(
effectController.ghue,
effectController.gsaturation,
effectController.glightness);

// Ambient lighting
ambientLight.color.setHSL(effectController.hue,
effectController.saturation,
effectController.lightness * effectController.ka);

light.position.set(effectController.lx,
effectController.ly, effectController.lz);
light.color.setHSL(effectController.lhue,
effectController.lsatisfaction,
effectController.llightness);

// Clear to background color
renderer.autoClear = true;
renderer.render( scene, camera );

// Rebuild from scratch
function createNewNebula() {

    if (bstars)
    {
        scene.add( stars );
    }
    else
    {
        scene.remove( stars );
    }

    if (bcluster)
    {
        scene.add( cluster );
    }
    else
    {
        scene.remove( cluster );
    }

    if (bgaia)
    {
        scene.add( gaia );
    }
    else
    {
        scene.remove( gaia );
    }

    if (innernebula !== undefined) {
        innernebula.geometry.dispose();
        scene.remove( innernebula );
    }

    if (outernebula !== undefined) {

outernebula.geometry.dispose();
scene.remove(outernebula);
}

// Scale is 1 GL unit = 1 parsec or 1 unit/pc
// Inner radius of the Rosette is set at 4.75 pc
// Outer radius of the Rosette is set at 12.44 pc
// These values are hard coded in the shader also

var innerGeometry = new THREE.SphereGeometry(4.75, 30, 30);
var outerGeometry = new THREE.SphereGeometry(12.44, 30, 30);

// Use finer grid to improve sampling for continuous glow

var glowingGeometry = new THREE.SphereGeometry(12.44, 200, 200);

if (binner)
{

if (shading != "glowing")
{
innernebula = new THREE.Mesh(innerGeometry,
  shading === "wireframe" ? wireMaterial :
  shading === "flat" ? flatMaterial :
  shading === "smooth" ? gouraudMaterial :
  shading === "glossy" ? phongMaterial :
  shading === "textured" ? texturedMaterial :
    phongMaterial)); // if no match, pick Phong
}
else
{
  //glowMaterial.side = THREE.FrontSide;
  //glowMaterial.side = THREE.BackSide;
  //glowMaterial.side = THREE.BothSides;
  this.innernebula = new THREE.Mesh(
    innerGeometry.clone(), glowMaterial);
}
scene.add(innernebula);

}

if (bouter) {

if (shading !== "glowing") {

outernebula = new THREE.Mesh(
    outerGeometry,
    shading === "wireframe" ? wireMaterial : (  
        shading === "flat" ? flatMaterial : (  
            shading === "smooth" ? gouraudMaterial : (  
                shading === "glossy" ? phongMaterial : (  
                    shading === "textured" ? texturedMaterial :  
                        phongMaterial ) ) ) ) ) ;  // if no match,  
    pick Phong

}
else {

    // glowMaterial.side = THREE.FrontSide;
    // glowMaterial.side = THREE.BackSide;
    glowMaterial.side = THREE.BothSides;
    this.outernebula = new THREE.Mesh(
        glowingGeometry.clone(), glowMaterial);
}

outernebula.renderOrder = 9;
scene.add(outernebula);

}

</script>

</body>
</html>

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Vita

Jeremy Huber

Education

Ph.D. Course Work in Physics, University of Virginia, Charlottesville, VA, No Degree

M.S. Physics, University of Louisville, Louisville, KY, August 2003

B.S. Mathematics and Physics, University of Louisville, Louisville, KY, May 2001

Professional Positions

Visiting Assistant Professor of Math and Physics, University of Cincinnati Blue Ash College, August 2015 - Present

Lecturer in Physics, Northern Kentucky University, January 2011 - June 2015

Graduate Research Assistant in Astrophysics, University of Louisville, August 2005 - August 2012

Honors and Awards


National Science Foundation Integrative Graduate Education and Research Trainee (IGERT) Fellowship, August 2003 - July 2005

Sigma Pi Sigma

Manuel B. Schwartz Award for Outstanding Graduate Achievement in Physics, Spring 2003

Donald M. Bennett Award for Outstanding Scholastic Achievement in Physics, Spring 2001

Publications and Presentations

Dust in the Rosette Nebula, J. Huber and J. F. Kielkopf, 223rd Meeting of the American Astronomical Society, Washington, D.C., January 5-9, 2014; American As-

